Overview of the Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science

Workshop on
Nuclear Reactions on Unstable Nuclei
and the
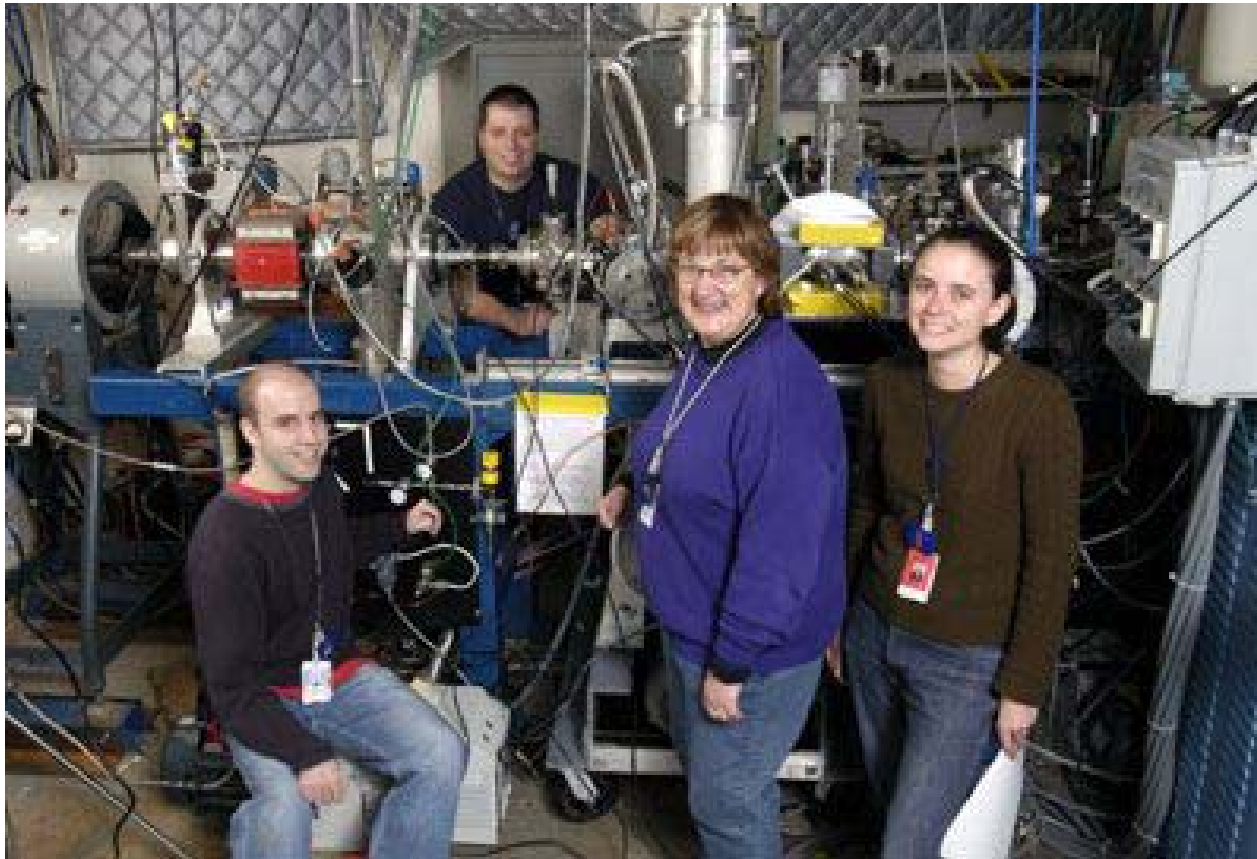Surrogate Reaction Technique

Jolie A. Cizewski

Rutgers University

The Center of Excellence: Consortium of Scientists

To measure surrogate reactions with unstable beams

- **Rutgers**
  - PI, JAC
  - Postdoc, 2 grad students, undergrads
- **UNIRIB/ORAU**
  - Consortium of Universities, mostly Southeast USA
  - Co-PI, Ken Carter; Ray Kozub (TTU)
  - 2 Postdocs, 1 Technician
  - Subcontracts to other (UNIRIB) Universities
    - Partial support Faculty, grad + undergrad students
- **ORNL**
  - Scientific staff + postdocs interested in transfer studies
- **NNSA Labs**
  - Livermore: John Becker, Lee Bernstein, Dennis McNabb, Mark Stoyer
  - Los Alamos: Matt Devlin, Stephanie Frankel

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Rutgers + ORAU participants

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Ion Source Developments

- ## Co-PI, Ken Carter, UNIRIB

  - ### Manager of sub-contract to UNIRIB

- ## Postdoc dedicated to ion source developments

- ## Expertise with UNISOR as test bench for ion source development

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NNSA Laboratories

- **Livermore National Lab**
  - John Becker, Lee Bernstein, Dennis McNabb, Mark Stoyer
- **Los Alamos National Lab**
  - Matt Devlin, Stephanie Frankel
- **Annual workshop at NNSA Lab**
  - 7-10 Center participants
  - First January 2004 at Livermore
- **Early career scientists $\Rightarrow$ pipeline to careers at NNSA Labs**

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Landscape of Neutron-rich Nuclei
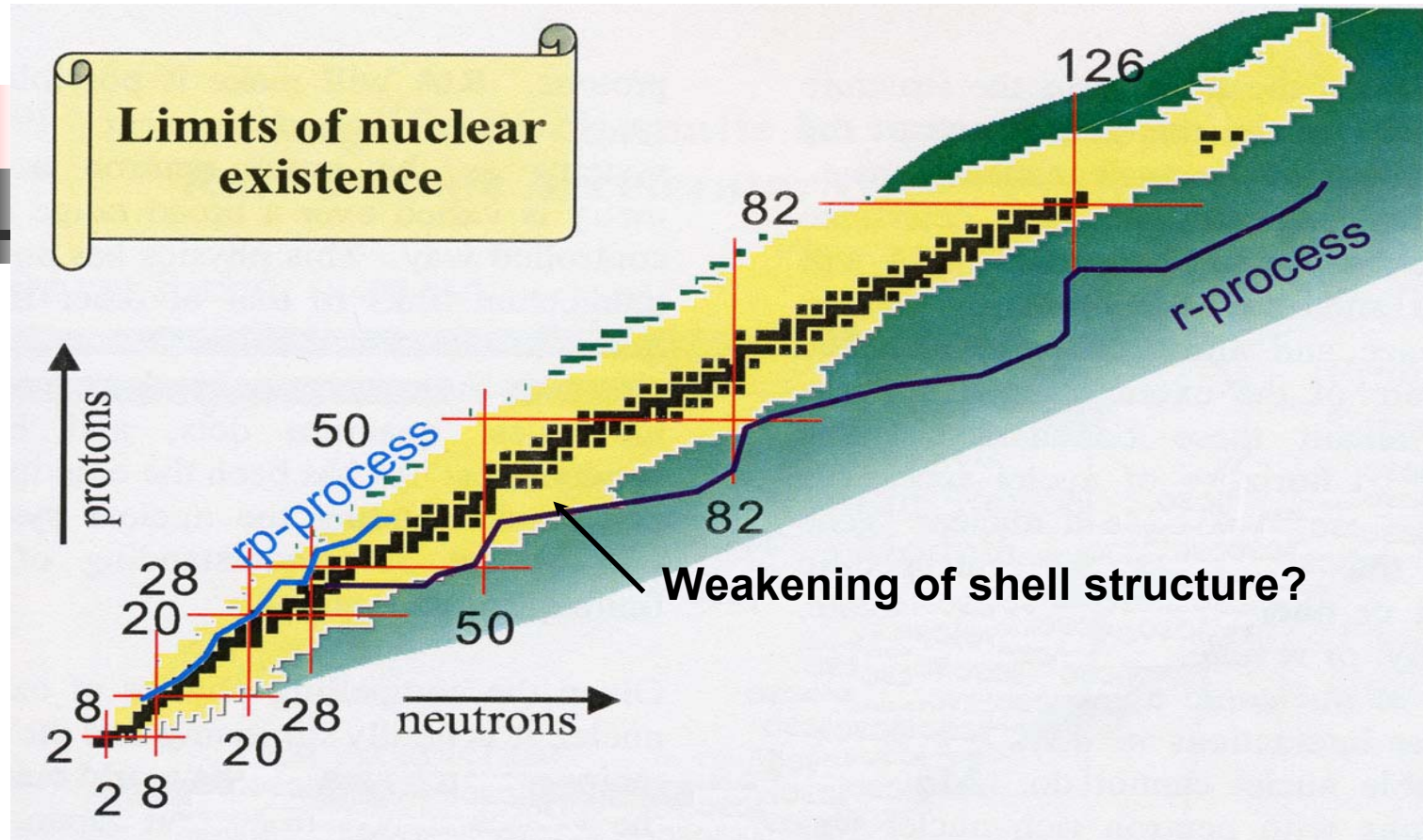
- Change in nuclear shell structure?
- Path of r-process nucleosynthesis
- Important for stockpile stewardship science
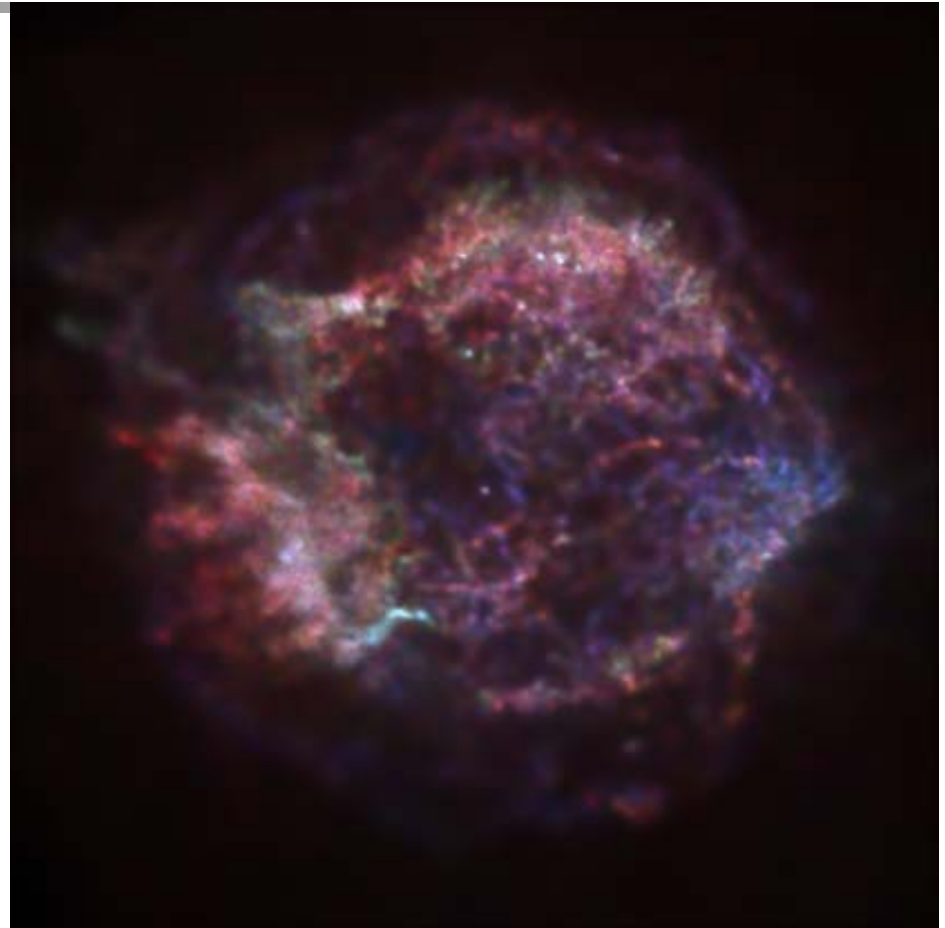- Direct (d,p) reaction measurements to inform all of these
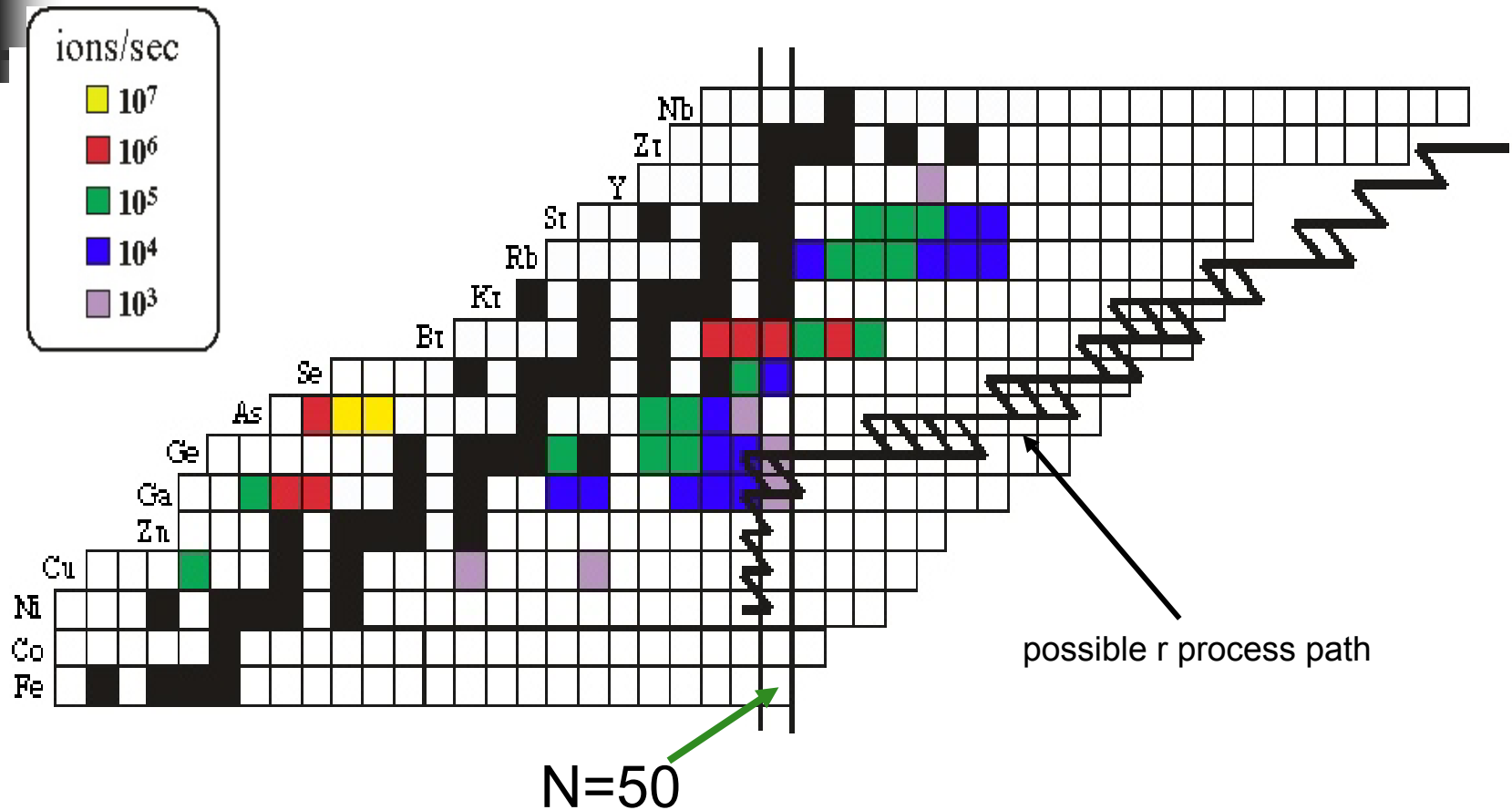
Approaching neutron drip line Change in shell structure?
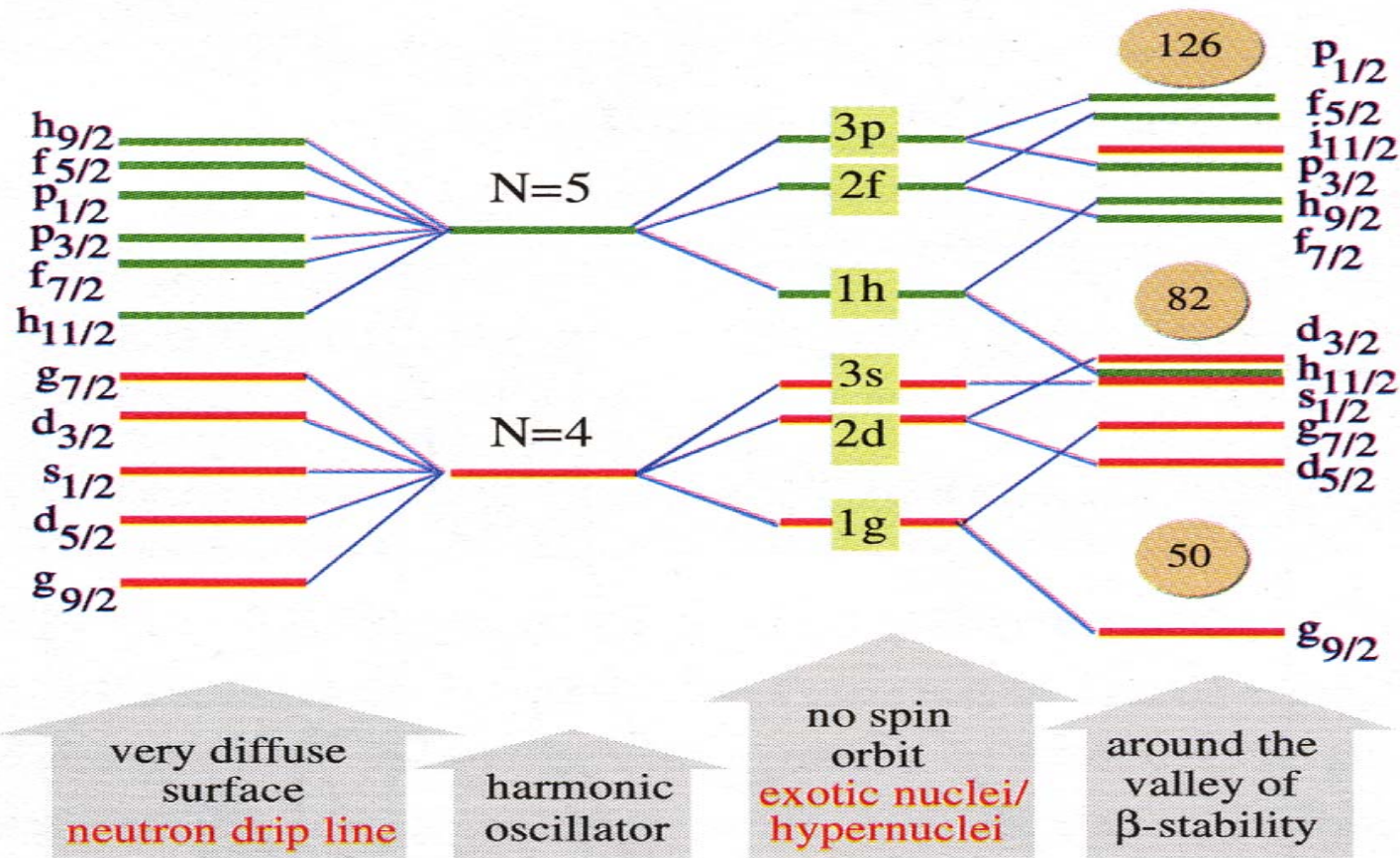
Neutron Rich Nuclei
r-process nucleosynthesis

•Multiple neutron captures in supernova explosions

•Proceed towards line where (n,γ)-(γ,n) equilibrium

•Waiting points when neutron capture rate slower than beta decay

January 2004

Neutron-rich N≈50 isotones
r-process path

possible r process path

N=50

(d,p) as surrogate for (n,γ) reaction

Example
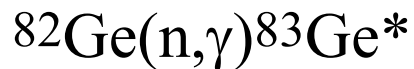
Desired reaction
^{82}Ge(n,γ)^{83}Ge*
$E_x \approx 4$ MeV
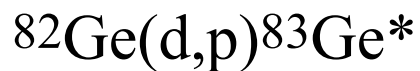
Surrogate reaction
^{82}Ge(d,p)^{83}Ge*
$E_x \approx 0\text{-}4$ MeV

Neutron Capture

S_n Near stability

many levels

neutron

$_Z A_N$

$_Z A+1_{N+1}$

Near n-dripline

neutron

S_n

$_Z A_N$

$_Z A+1_{N+1}$

(d,p) Reaction

$_Z A+1_{N+1}$
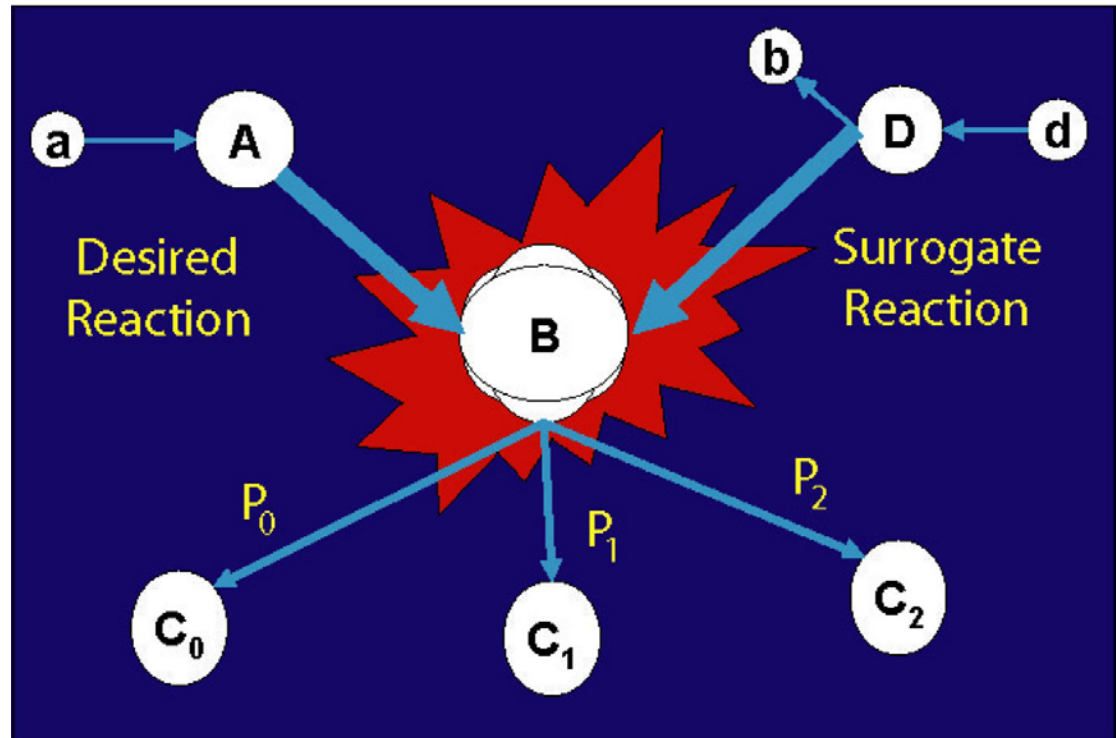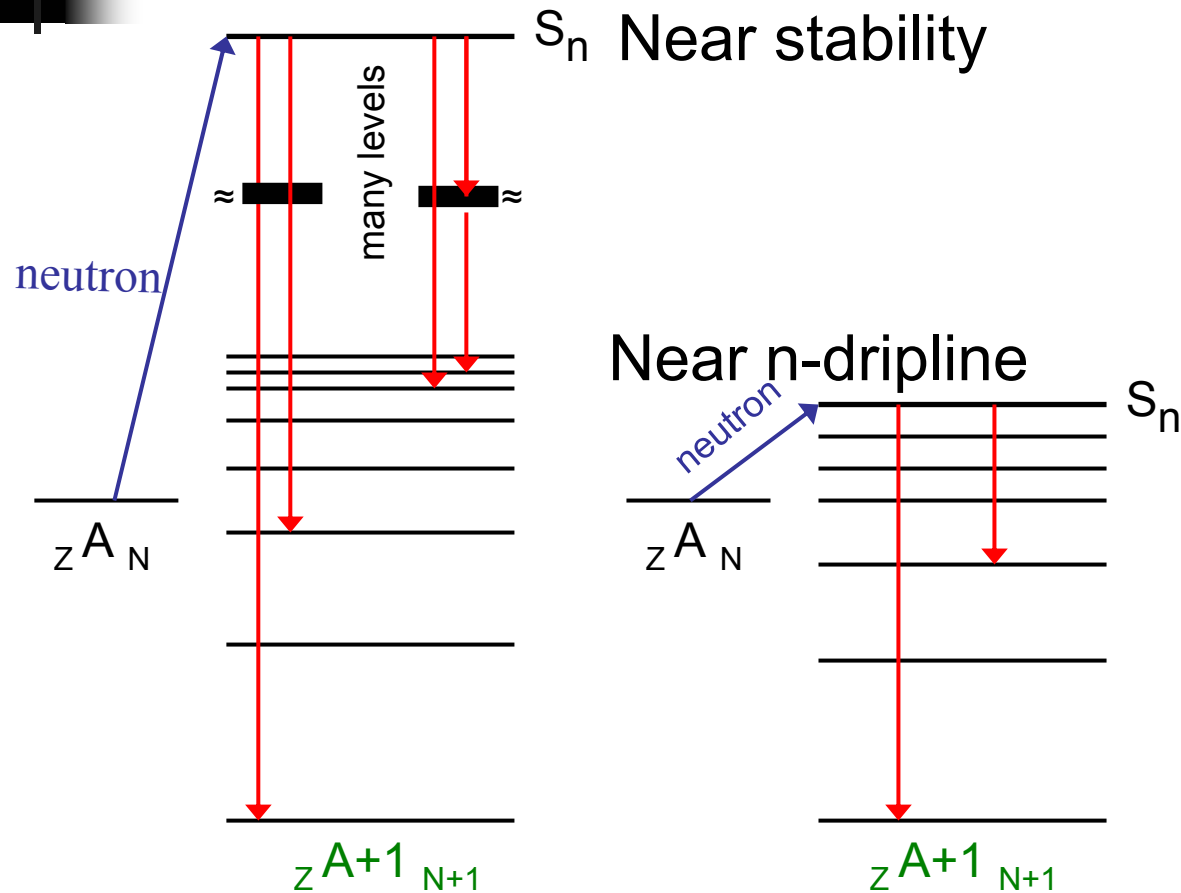
$_Z A_N$
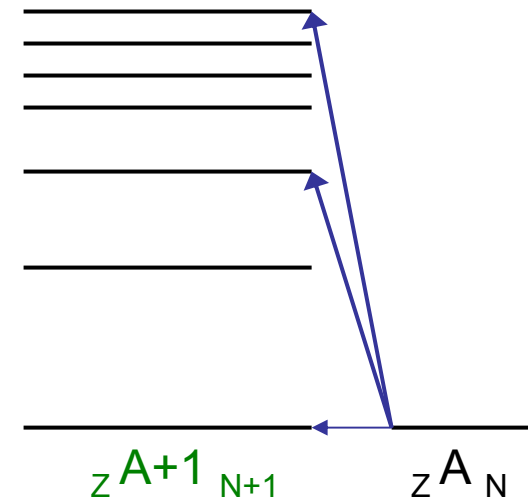
Direct Capture

Thermal capture

S_n

(1/2-,3/2-)

3/2-

1/2-

3/2-

3/2-

$_Z A_N$

$_Z A+1_{N+1}$

neutron

(d,p)

$_Z A_{N+1}$

$_Z A_{N+1}$
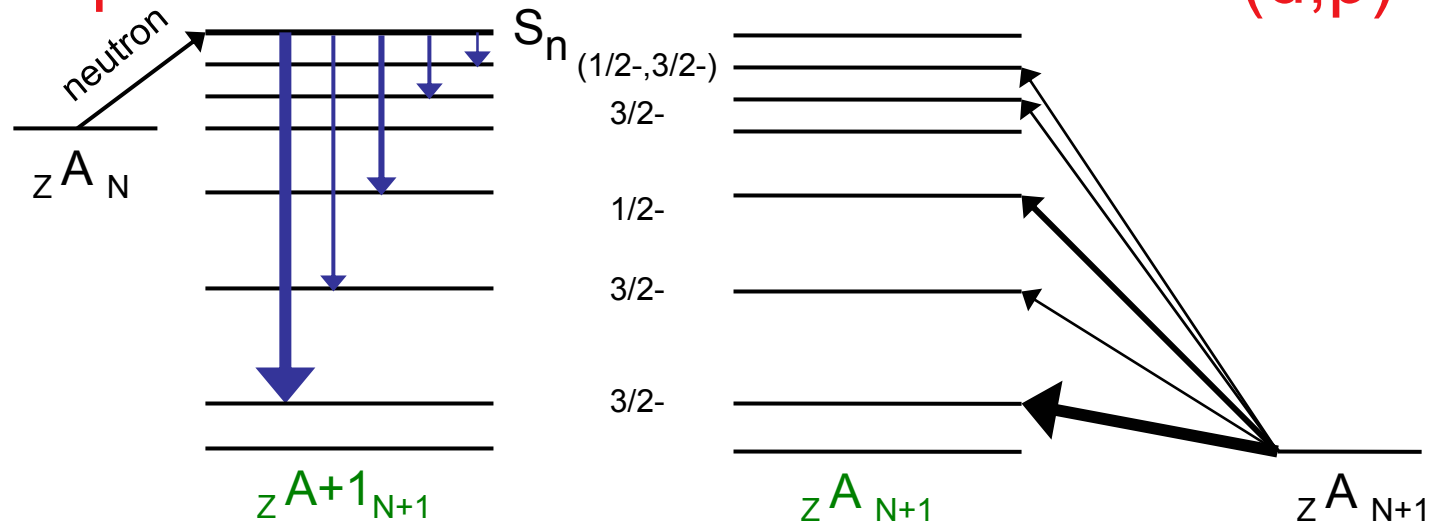
$$\sigma_\gamma \approx (2J+1) \text{ Spectroscopic factor}$$

In general would expect Direct + Non-Direct (resonant?) processes
Require theoretical guidance

Challenges for (n,γ) Cross section Determinations

- **Intermediate products far from stability**
  - Short half-lives,e.g., $t_{1/2}$ (^{82}Ge) = 4.6s
  - Can't measure directly
- **Difficult to predict (n,γ) cross sections**
  - Can't use results for stable nuclei when far from stability, especially N>>Z
  - Low neutron separation energies, S_n
  - Low level density near S_n low
  - Reaction? Direct processes?
- **(d,p) reactions provide input to modeling**
- **(d,p) provides direct measure of single-neutron properties**
- **When direct capture, σ(d,p) $\propto$ σ(n,γ)**

Measuring (d,p), on unstable species

- *Beams* of unstable species rather than stable *targets*
- Can measure beams with $t_{1/2} > 1$ second
- Capability at Oak Ridge National Laboratory
  - Produce unstable beams of ^{238}U fission fragments
  - Use deuterated plastic targets
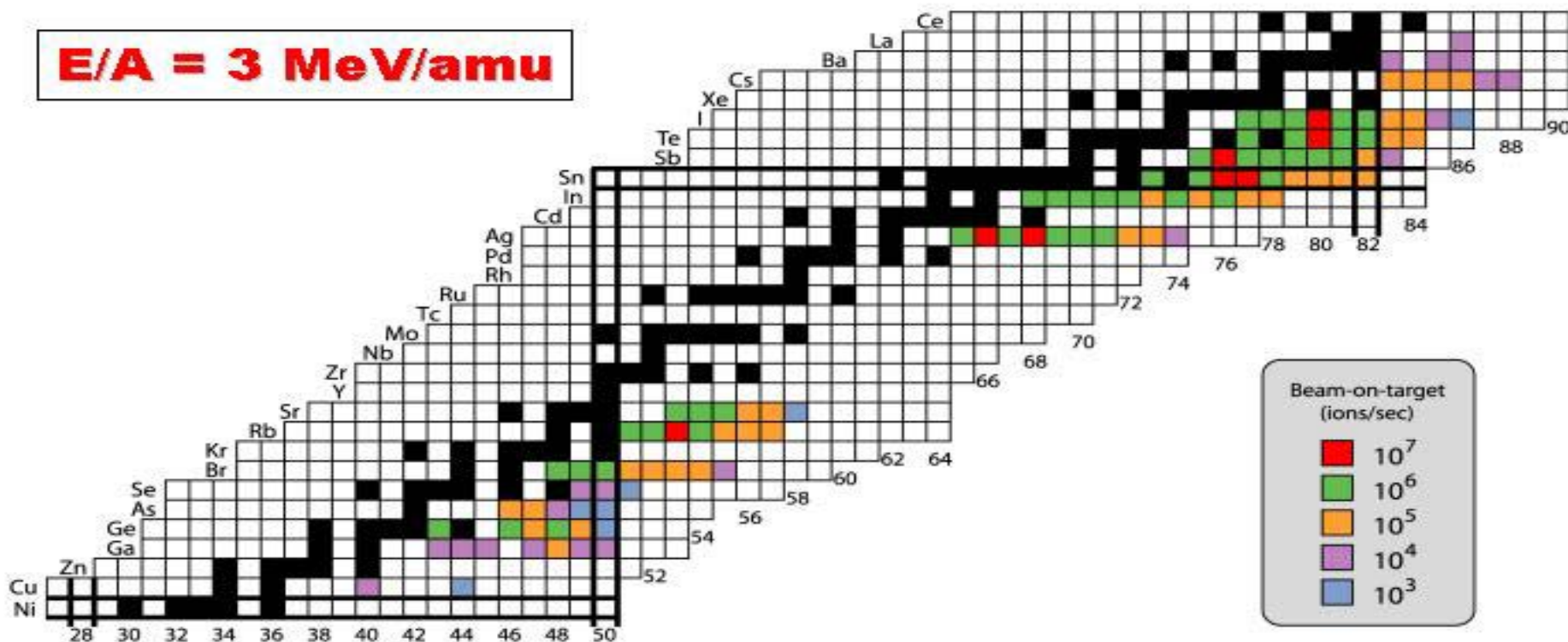 - Measure reaction protons
  - Measure beam-like species
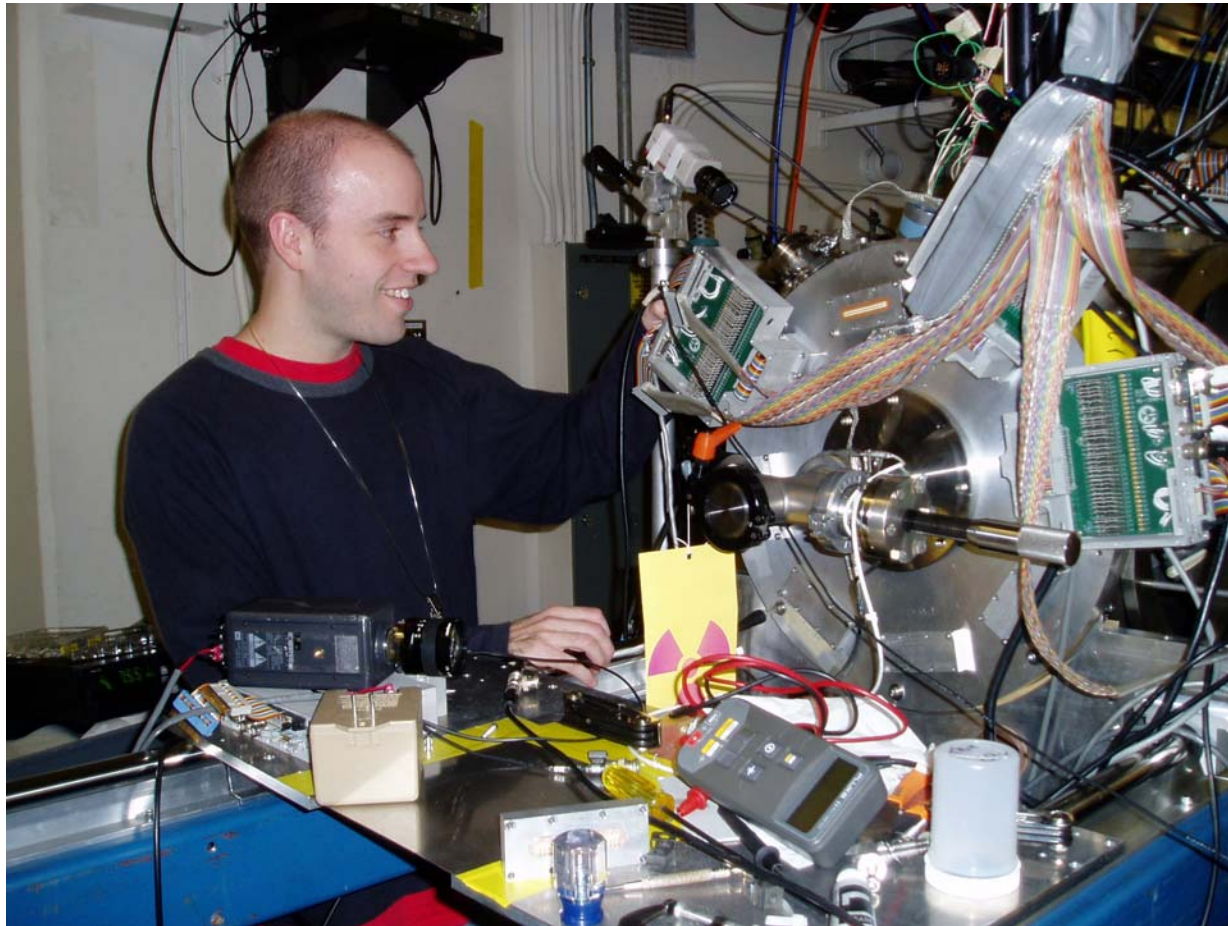
Holifield Radioactive Ion Beam Facility
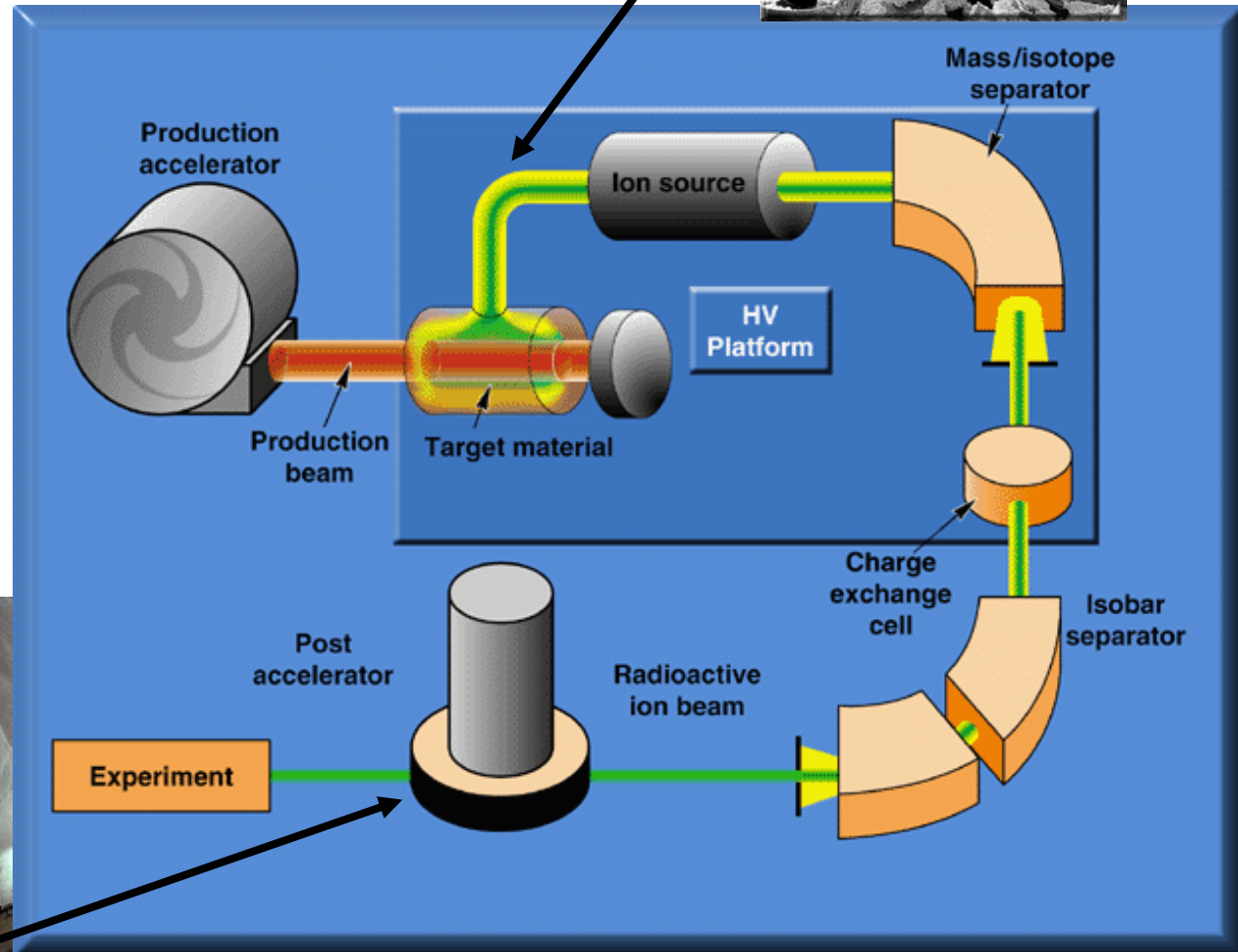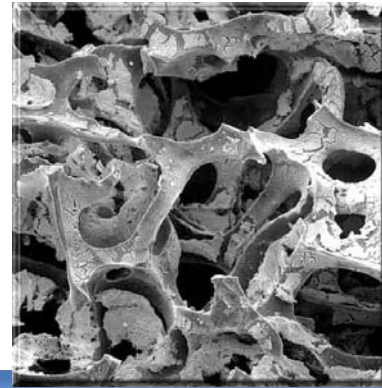
Neutron-rich Beams at HRIBF

Accelerated Neutron-rich Radioactive Ion Beams
(over 100 beams with intensities ≥10^3 ions/sec)

$E/A = 3$ MeV/amu
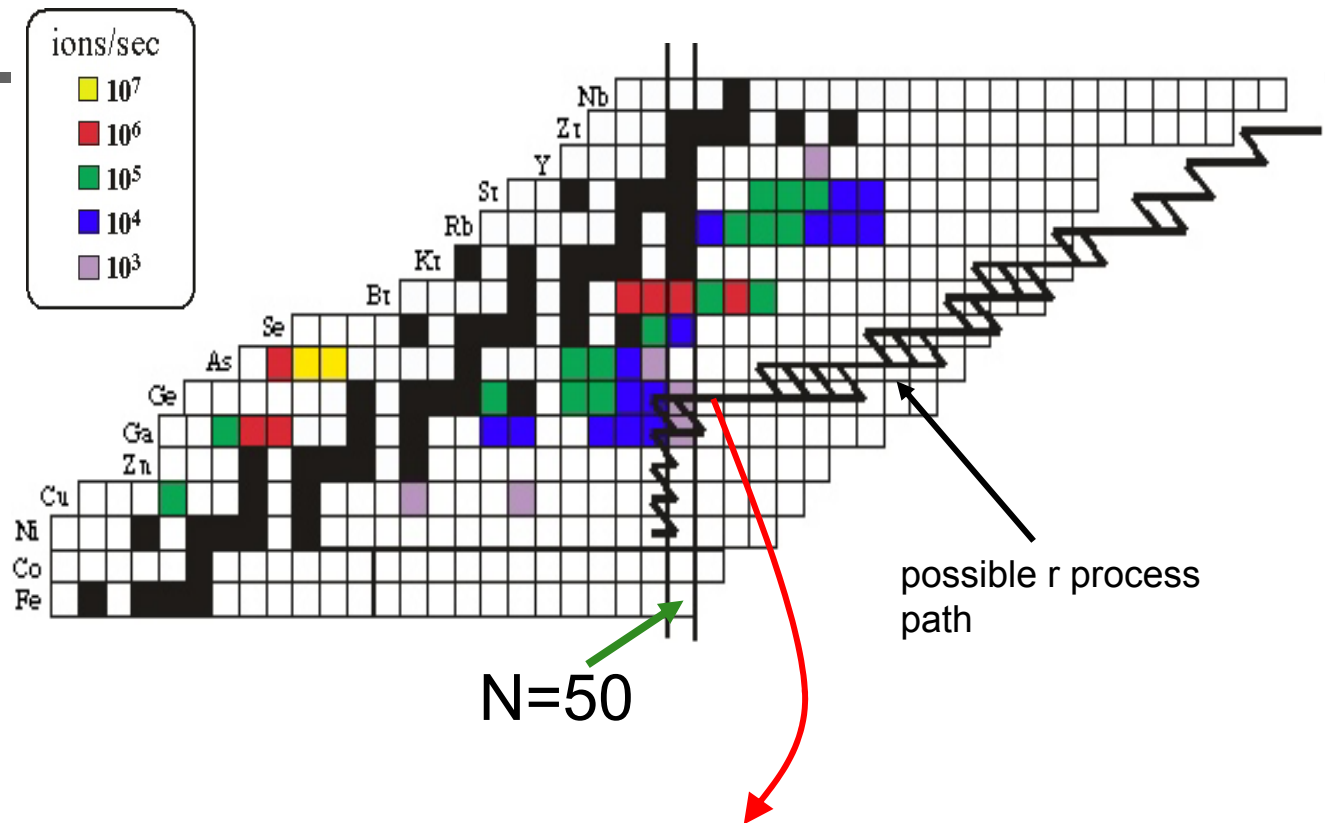
Beam-on-target (ions/sec)

- 10^7 (red)
- 10^6 (green)
- 10^5 (orange)
- 10^4 (purple)
- 10^3 (blue)

First Measurements: d(^{82}Ge,p)

Jeff Thomas -
Back at Oak Ridge measuring surrogate reaction with ^{84}Se beam

^{82}Ge(d,p)
Neutron-rich N=51 isotones, r-process path

possible r process path

N=50

^{83}Ge: $t_{1/2}$ only previous known property

Winger, J.A. *et al.*, Phys. Rev. C 38, 285 (1988)

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cm frame

I = 0
I = 2

$\sigma/d\Omega$(mb/sr)

θ_{cm}

(d,p) Reactions in Inverse Kinematics
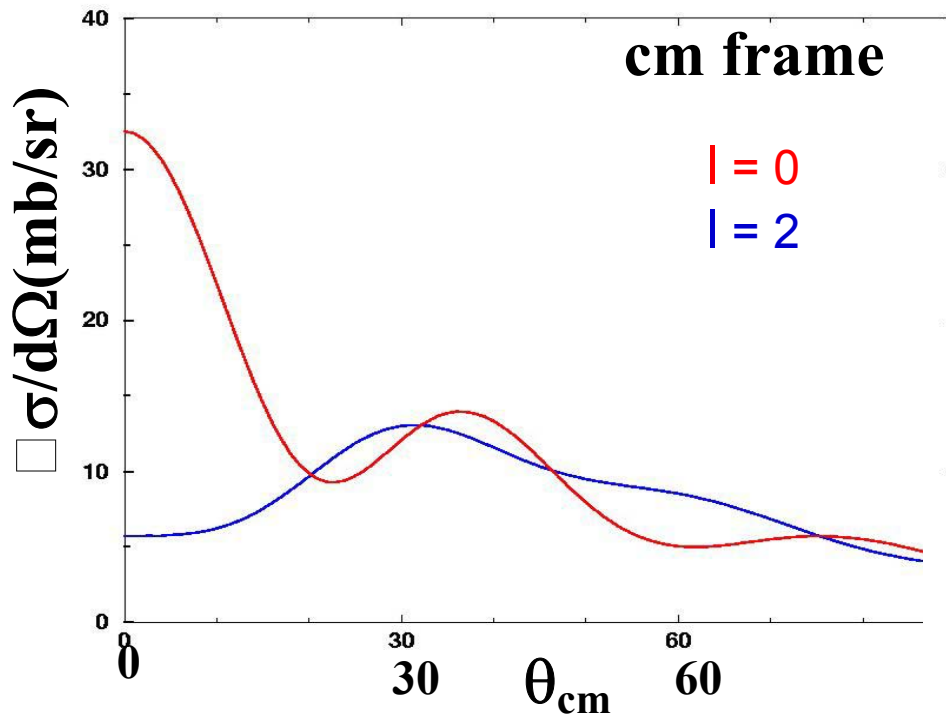
^{82}Ge(d,p)^{83}Ge
4 MeV/u

Forward θ_{cm} ↔ Back θ_{lab}
Low E_p at back angles

Lab frame

I = 0
I = 2

$\sigma/d\Omega$(mb/sr)

θ_{lab}
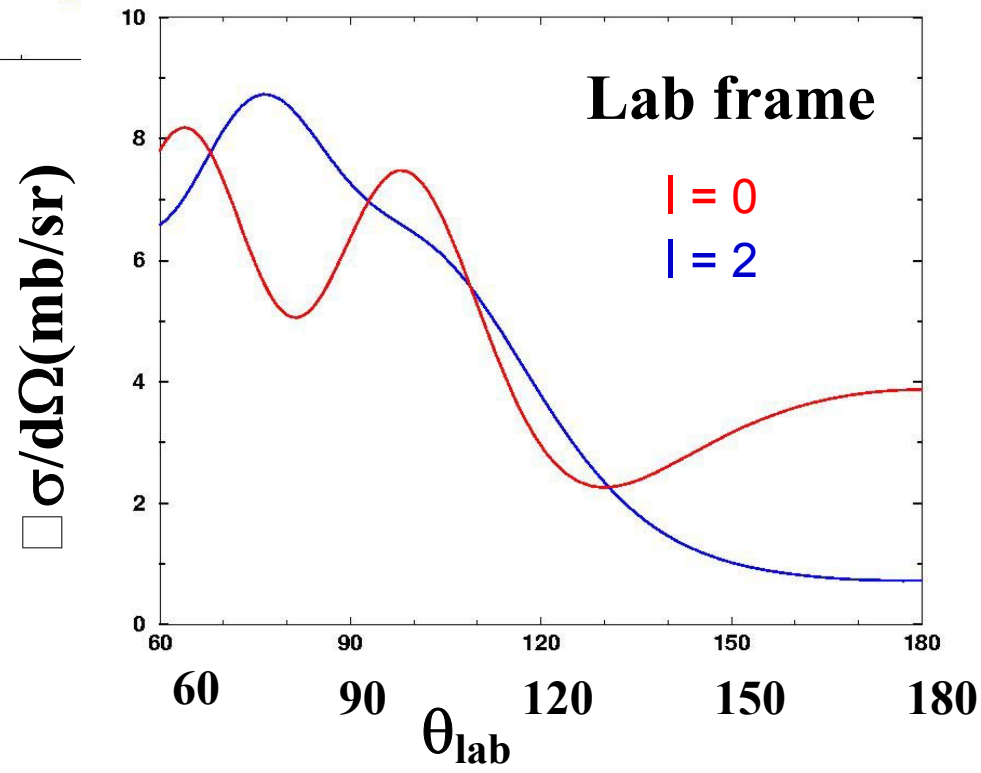
Initial measurements: (d,p) reactions on N=50 ^{82}Ge

- Enriched ^{82}Ge beam
  - Isobaric contaminant - ^{82}Se
- ≈430 μg/cm^2 CD$_2$ target
- Heavy recoil detection
  - Ion chamber - Z identification
  - In coincidence with light recoil
- Light recoil detection
  - Array of Si strip detectors
  - Back angles in the lab = forward angles in cm
    - Angle coverage 150<θ<110
  - E(proton), Angle(proton)
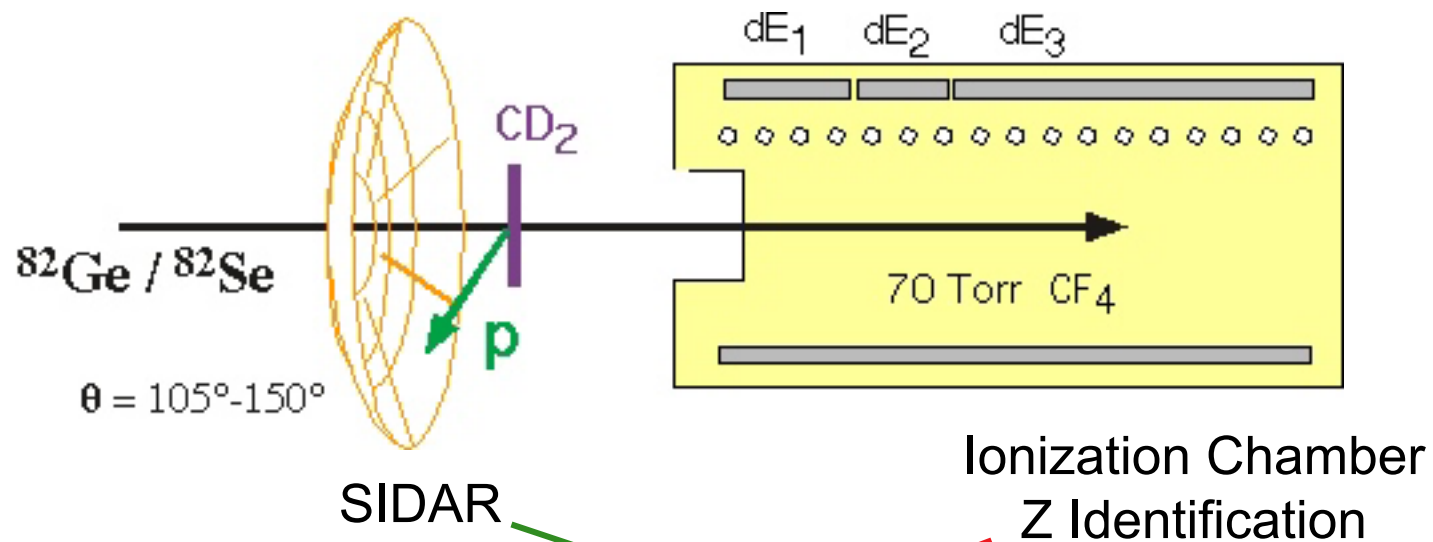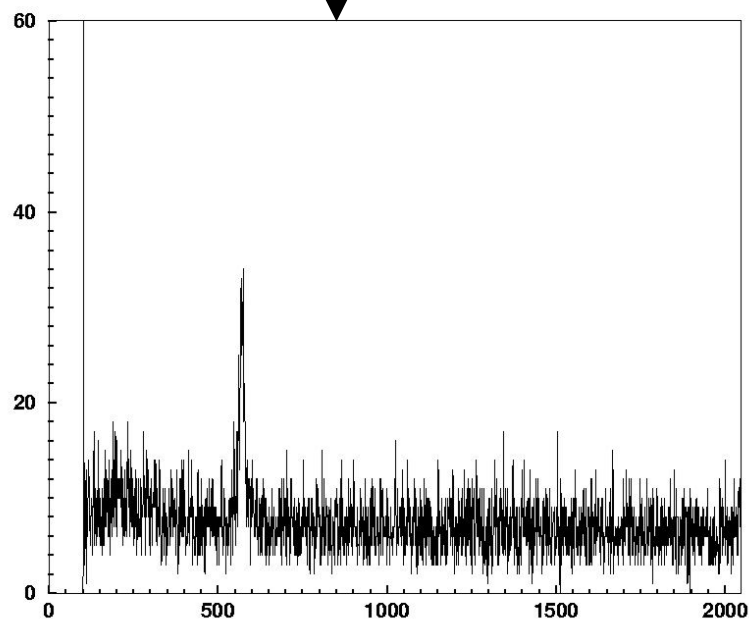
SIDAR - to detect light ions

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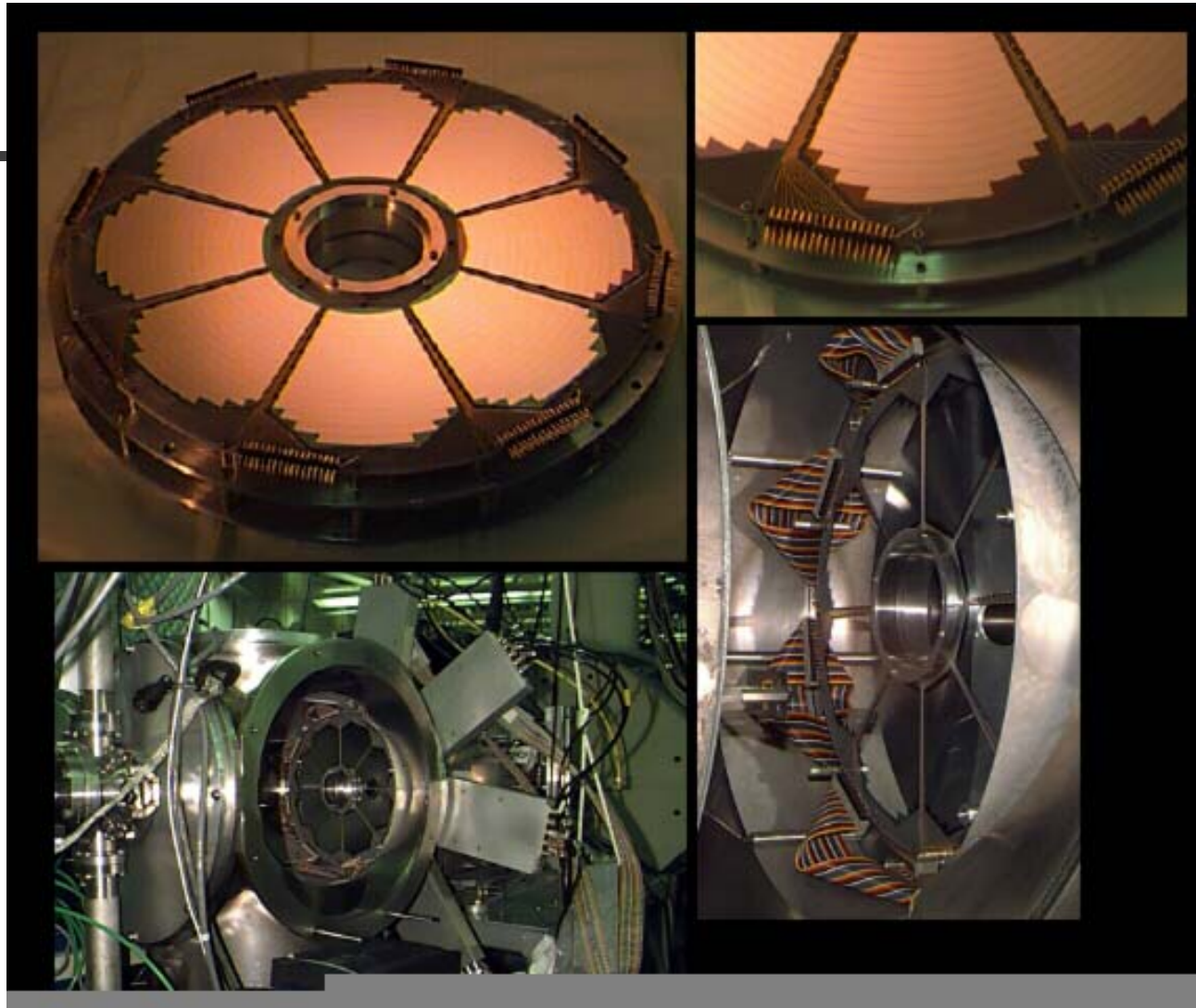
Ionization Chamber Performance

ΔE

Less than 10% pile-up
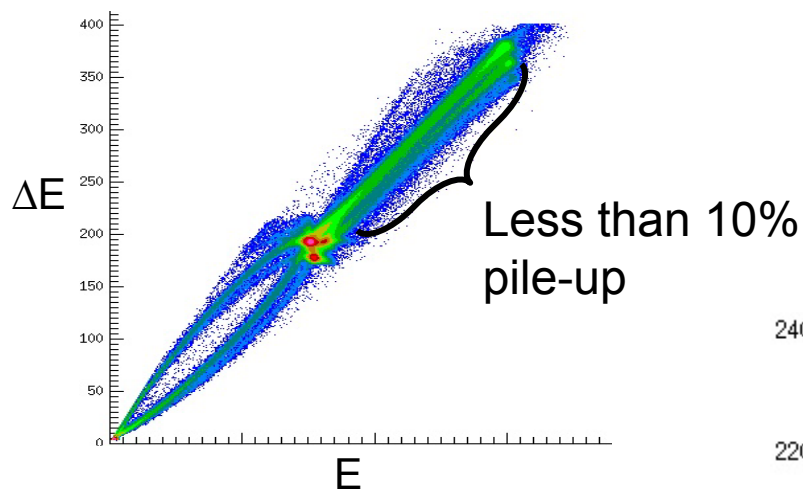
• ΔZ = 1 separation

1×10^4 Ge/s

6×10^4 Se/s

$< 1\times10^3$ As/s

ΔE

Se

As

Ge
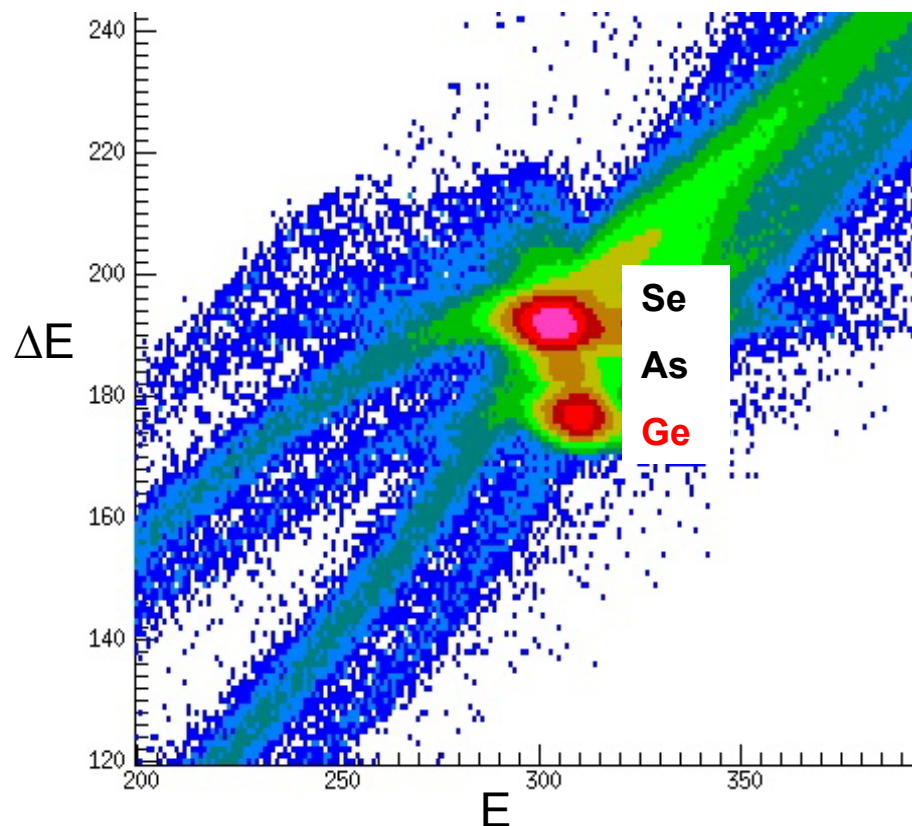
Calibration from d(^{82}Se,p)^{83}Se

- States are known – Montestruque, *et al.* Nucl. Phys. A305, 29 (1978)

≈2.5 MeV

≈550 keV

- Doublet at E_x = 540+582 keV

- FWHM ≈ 310 keV
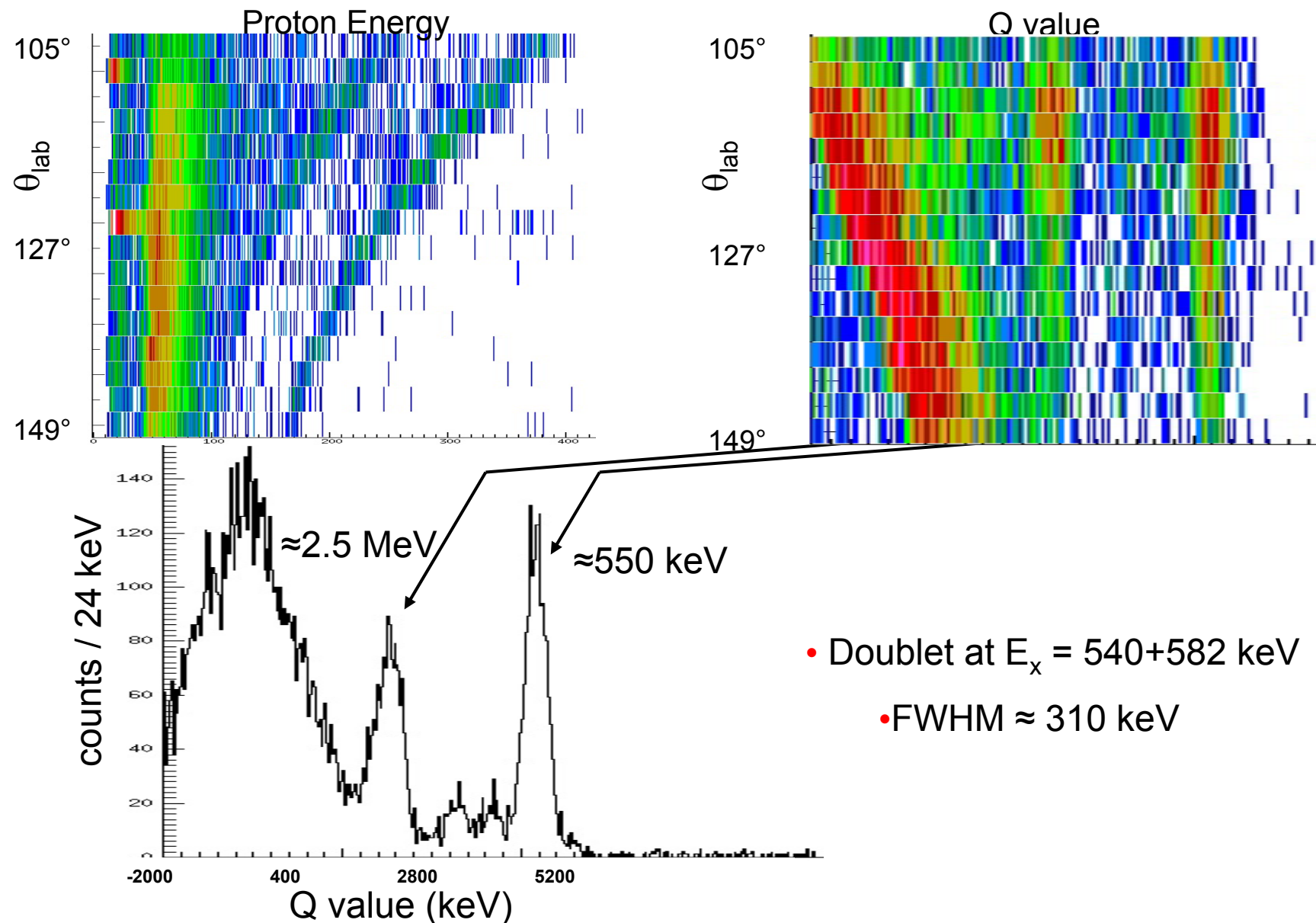
Preliminary ^{83}Ge Results
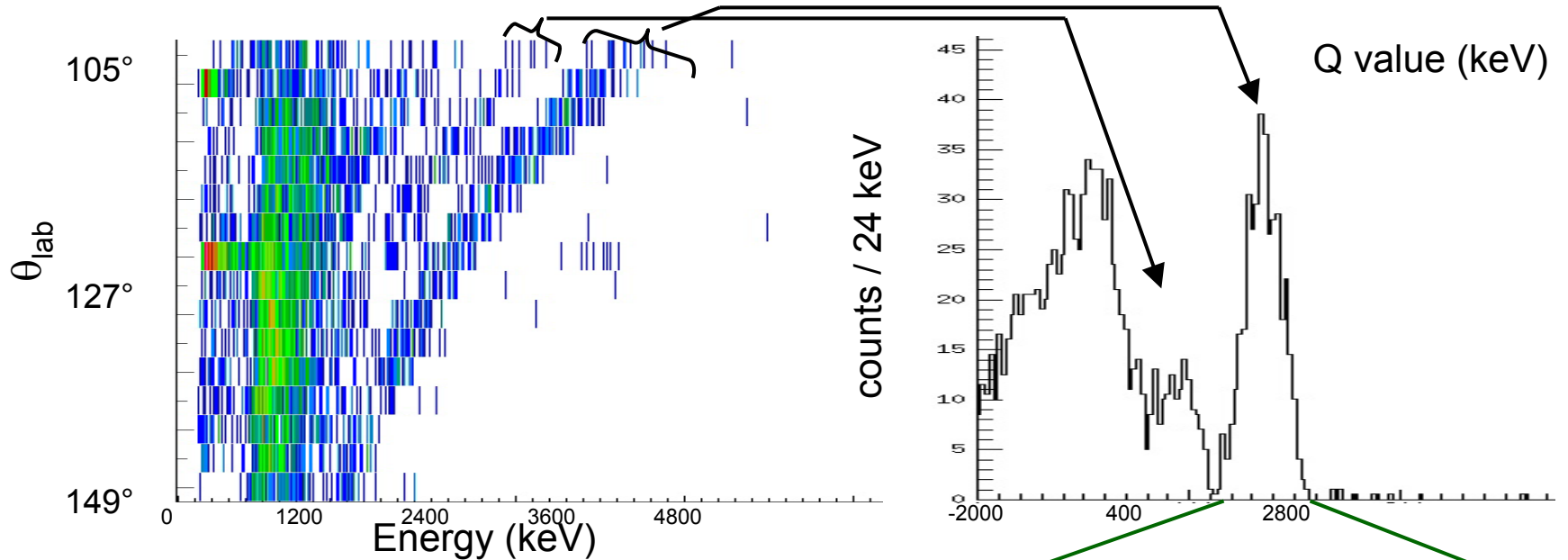
- Data summed over all detectors, all strips

- First Group FWHM ≈ 460 keV

- Fit assumes FWHM from ^{83}Se data (≈ 310 keV)

Q = 1.47 ($\pm$0.02 stat., $\pm$0.06 sys.) MeV

1st E_x = 260 ($\pm$ 20 stat.) keV
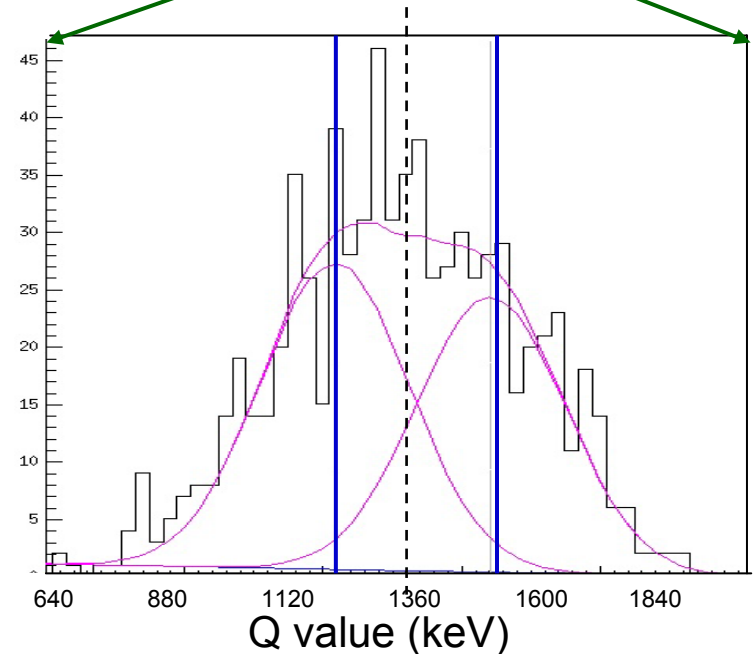
Preliminary ^{83}Ge Results
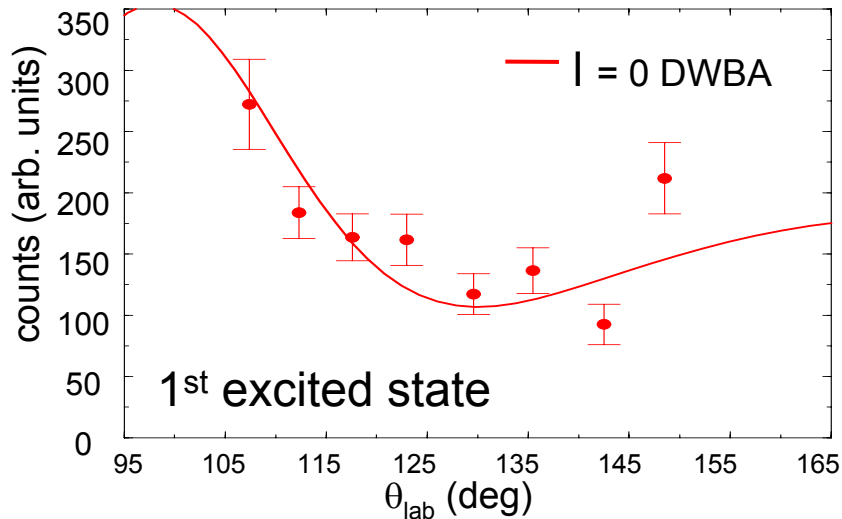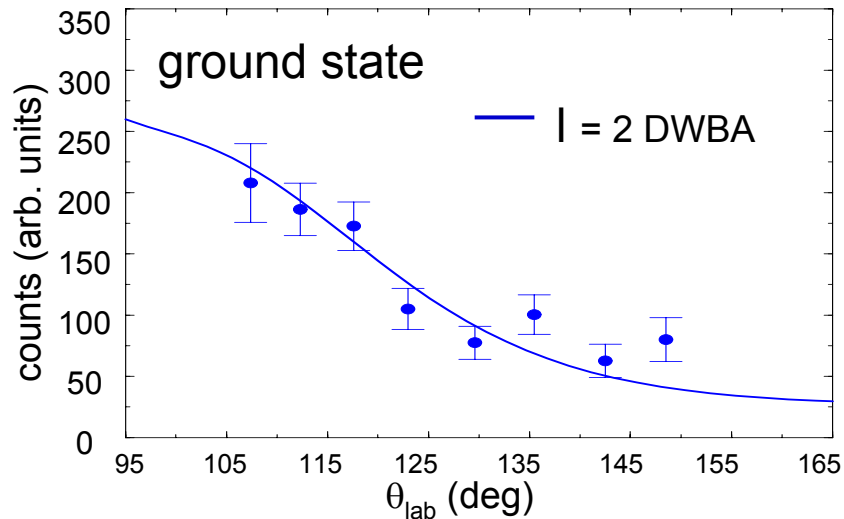
Angular distribution data
- 2 strip bins
- Doublet divided in half
- Curves = best fit to data

DWBA DWUCK5
- Global optical model params
  - d Lohr + Haberli
  - p Perey

- Ground state I=2
  - Presumably $d_{5/2}$

- 260 keV state I=0
  - $s_{1/2}$

Single-particle levels in N=51 isotones

N=51 Spectroscopic Strengths

spectroscopic factors indicated by length of bar
— this work (preliminary)
— previous work

E_x (MeV)

^{83}Ge ^{85}Se ^{87}Kr ^{89}Sr ^{91}Zr

$1/2^+$

$5/2^+$
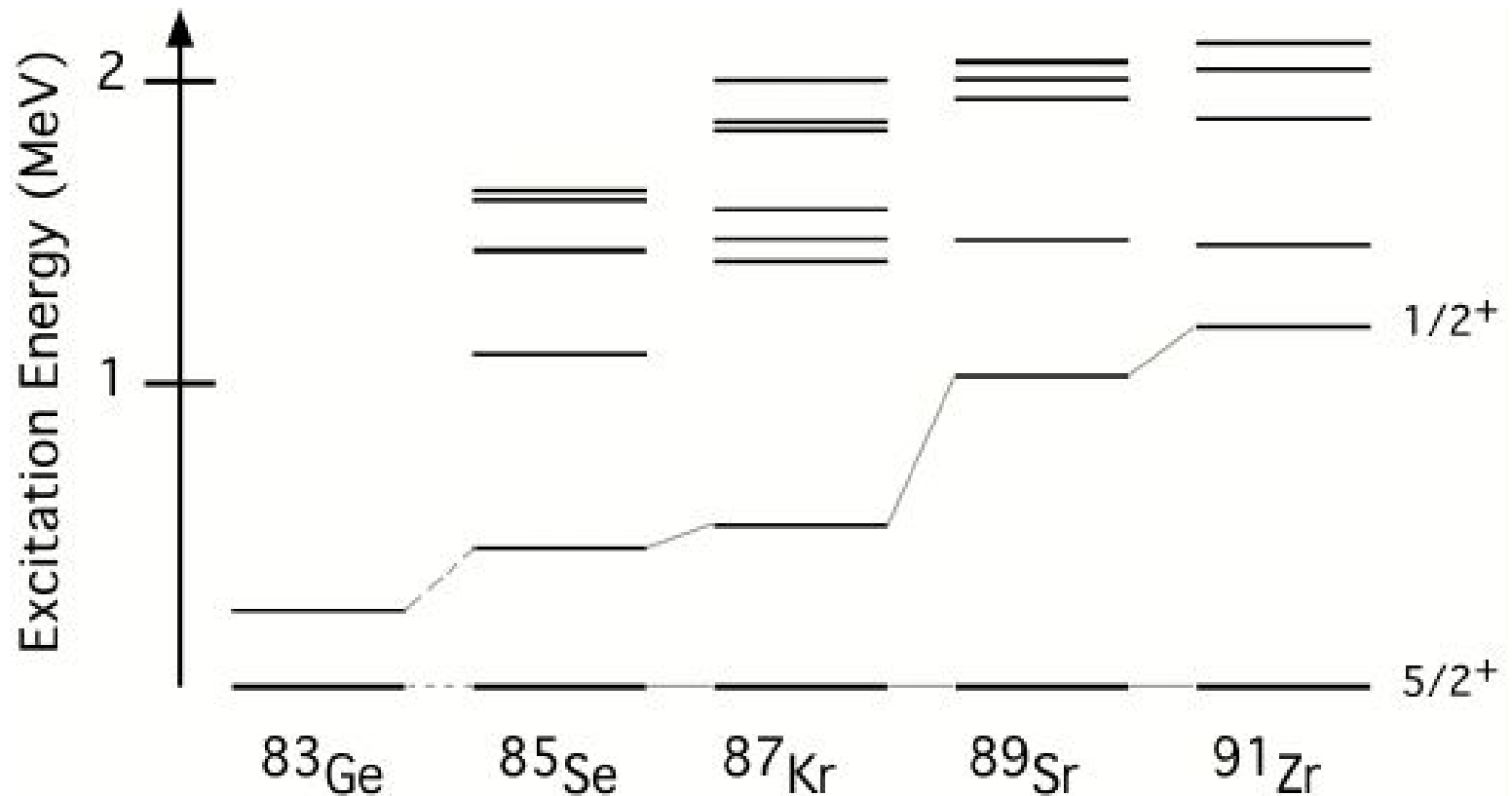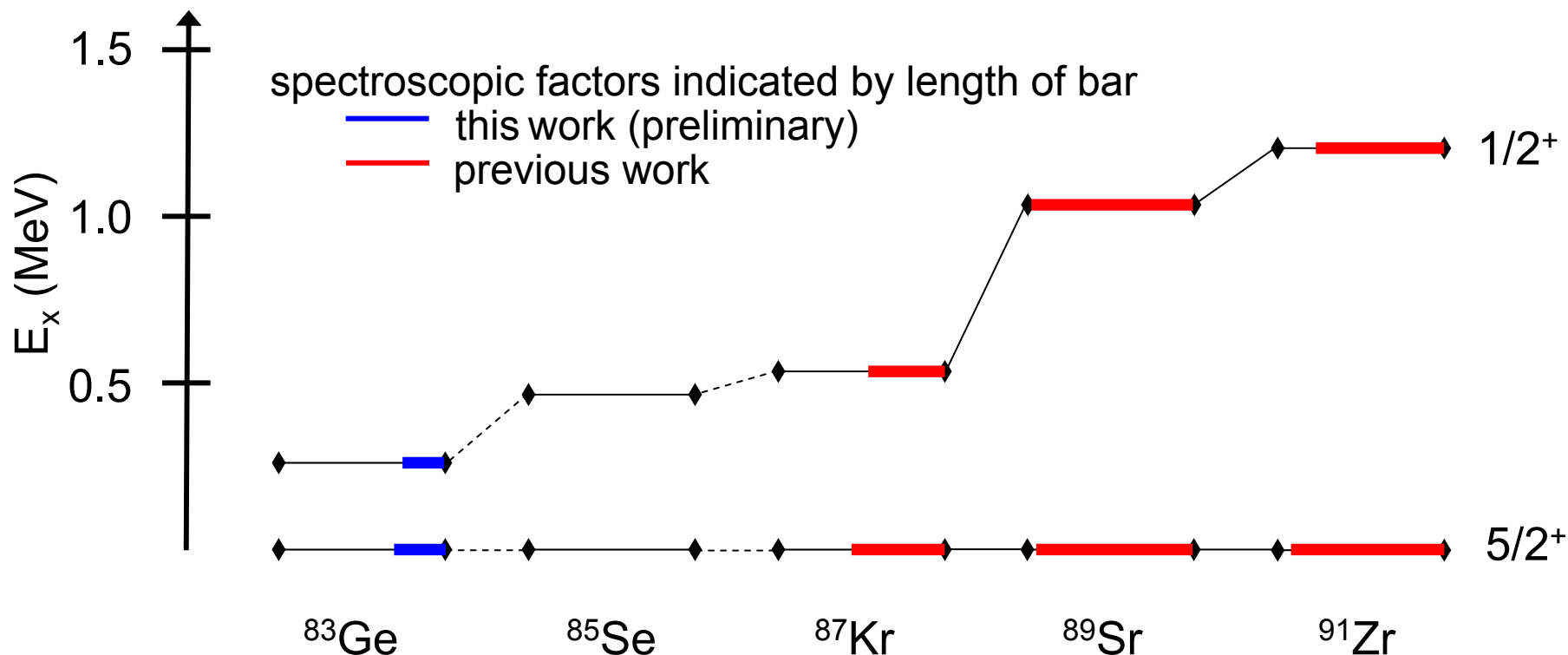
^{85}Se: J.P. Omtvedt, *et al*. Z. Phys. A **339**, 349 (1991).

^{87}Kr: K. Haravu, *et al*. Phys. Rev. C **1**, 938 (1970).

^{89}Sr: T.P. Cleary, Nucl. Phys. **A301**, 317 (1978).

A. Saganek, *et al*. J. Phys. **G10**, 549 (1984).

^{91}Zr: R.D. Rathmell, *et al*. Nucl. Phys. **A206**, 459 (1973).

H.P. Blok, *et al*. Nucl. Phys. **A273**, 142 (1976).

Spectroscopy of n-rich N=50 isotones

- ^{82}Ge(d,p)^{83}Ge (preliminary)
  - Q-value = 1.47(6) MeV, S_n = 3.7 MeV
  - $5/2^+$ ground state, *S*=0.25
  - $1/2^+$ state at 260(20) keV, *S*=0.31
- Alex Brown preliminary calculations, ^{78}Ni core
  - S_n = 4.1 MeV
  - $5/2^+$ ground state, *S* = 0.85
  - $1/2^+$ state at 470(200) keV, *S* = 0.51
- Next step (today) ^{84}Se(d,p)^{85}Se
  - To confirm angular momentum assignments
  - To measure spectroscopic strengths

Prospects for d(^{130,132}Sn,p)
This afternoon by Kate Jones

- **Measurements with ^{130,132}Sn beams**
  - To determine spectroscopic properties N>82
  - Important for r-process nucleosynthesis
  - Fission fragment, important for stewardship science

Prospects for d(^{130,132}Sn,p)
This afternoon by Kate Jones
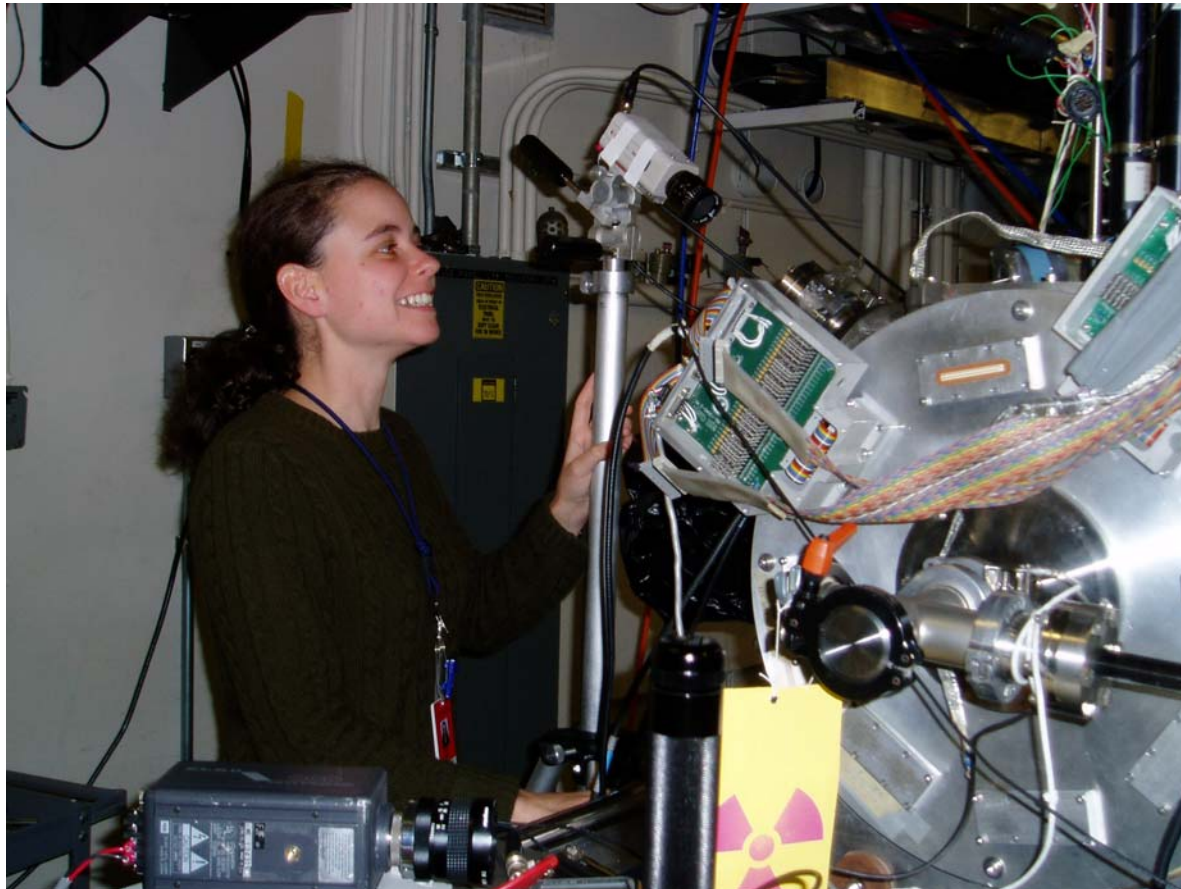
Angular distributions for d(132Sn,p) reaction

^{132}Sn(d,p) at 5 MeV/A

DWBA calculations

Legend:
- gs 2f7/2
- 1st ex 3p3/2
- 2nd ex 1h9/2
- 3rd ex 3p1/2
- 4th ex 2f5/2

y-axis: $d\sigma/d\Omega$ (mb/sr)

x-axis: θ_{lab} (degrees)

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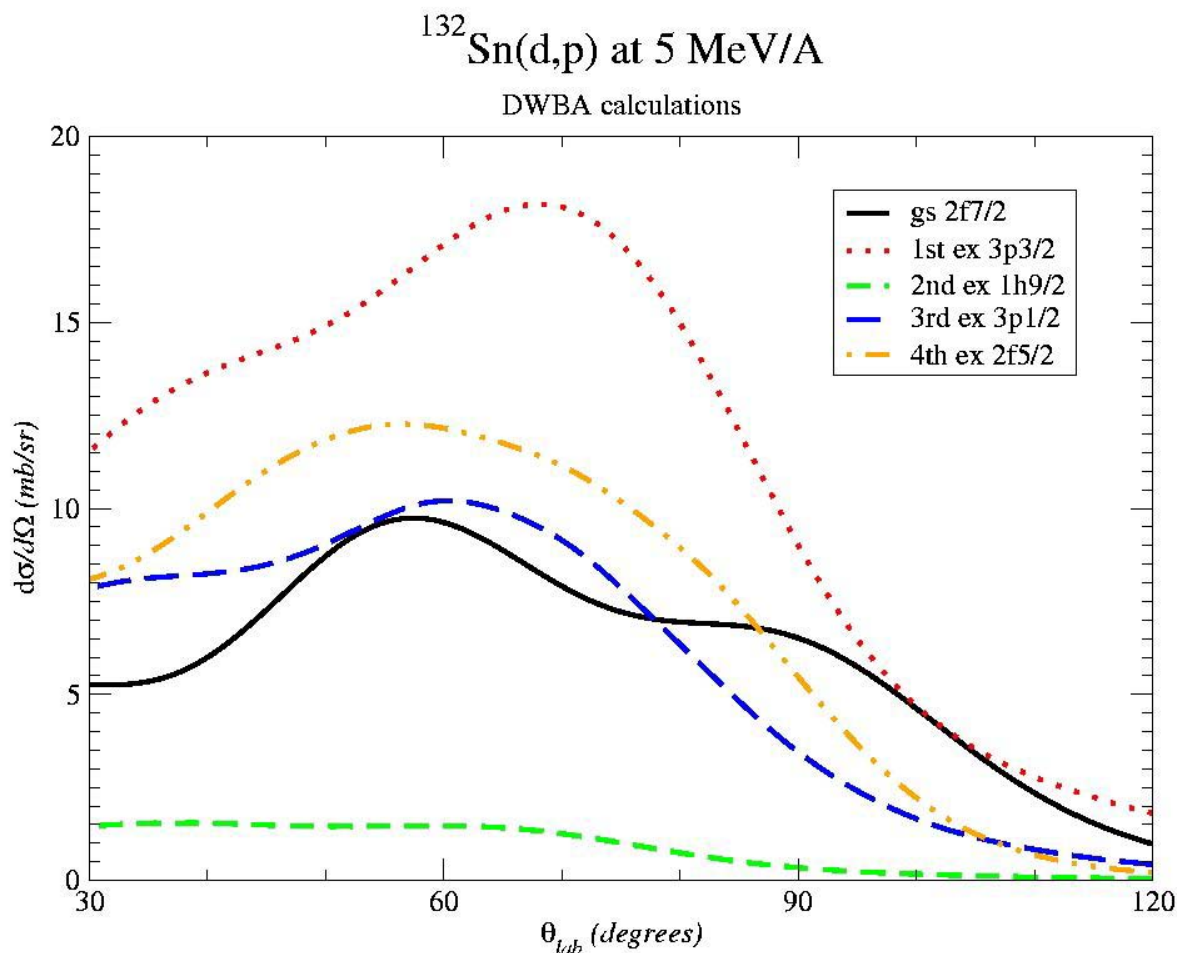
To measure A>90 (d,p) reactions

- ## Need to measure protons at $\theta \approx 90°$
- ## Challenge
  - ### Need light particle identification
    - To separate reaction p from target d
    - Variation in proton energies
- ## Flexible design
  - ### Useful for A≈130, A≈90
- ## Barrel array of Si strip ΔE-E detectors

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Detector Array for Transfer Reactions
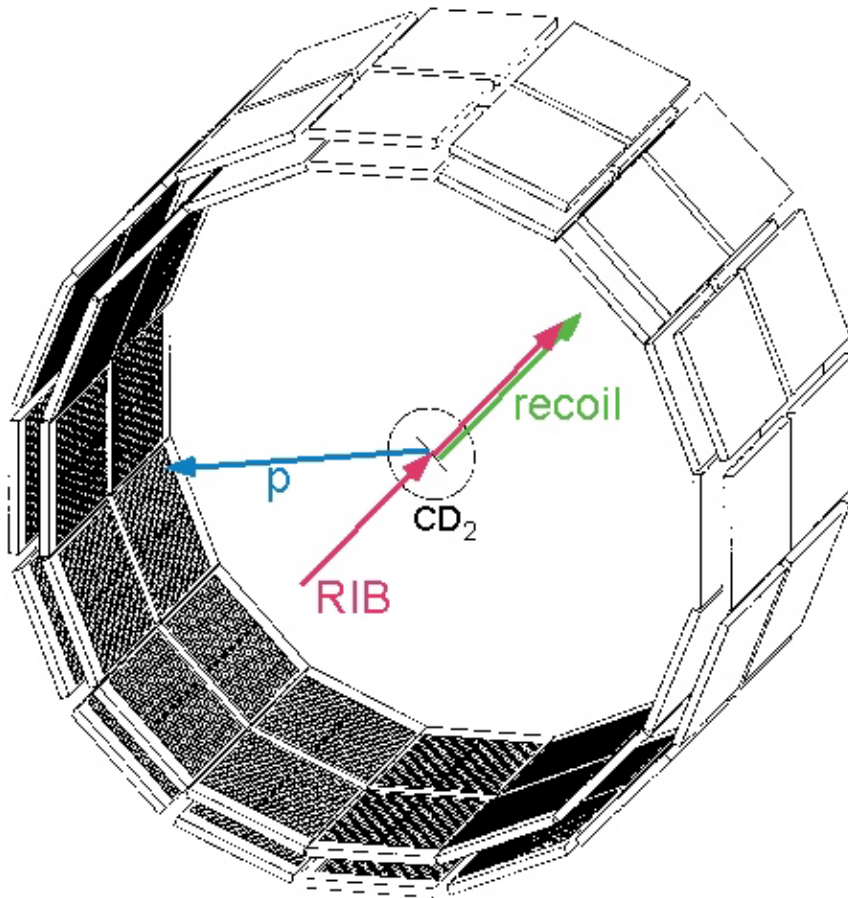
- **Primary use**
  - (d,p) with fission fragments
- **Desired properties**
  - High efficiency
  - Good resolution
  - Compatible with existing devices
  - Flexible
- **Goal**
  - Fully operation in early 2005
- **Funding**
  - ≈$600K over 3 years

- 2 Rings of ΔE-E Silicon telescopes
  - ΔE Position-sensitive, strip detectors, variable thickness
  - Shown here: 8.7 cm from target, 60° < θ < 120°

- Barrel Array of silicon detectors

- 2 cylinders of 16 Si detector telescopes
  - ΔE Position sensitive, strip detector
    - "thick" at forward q, "thin" at backward q
  - E thick (≈1000μm) Si detector

- Flexible configuration; Shown here
  - 8.7 cm from target, 60° < q < 120°

Barrel Array of Silicon Detectors

- Basic detector concept sound

- Position-sensitive detectors needed
  - Good angular resolution at modest cost
  - Count rates not a problem at our RIB intensities

- Need pure beams or Heavy Z Identification

- Proton particle identification provides clean channel selection

- Will need larger angular coverage for some experiments

- Target thickness should be optimized with detector specs

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Timeline for Detector Array Development
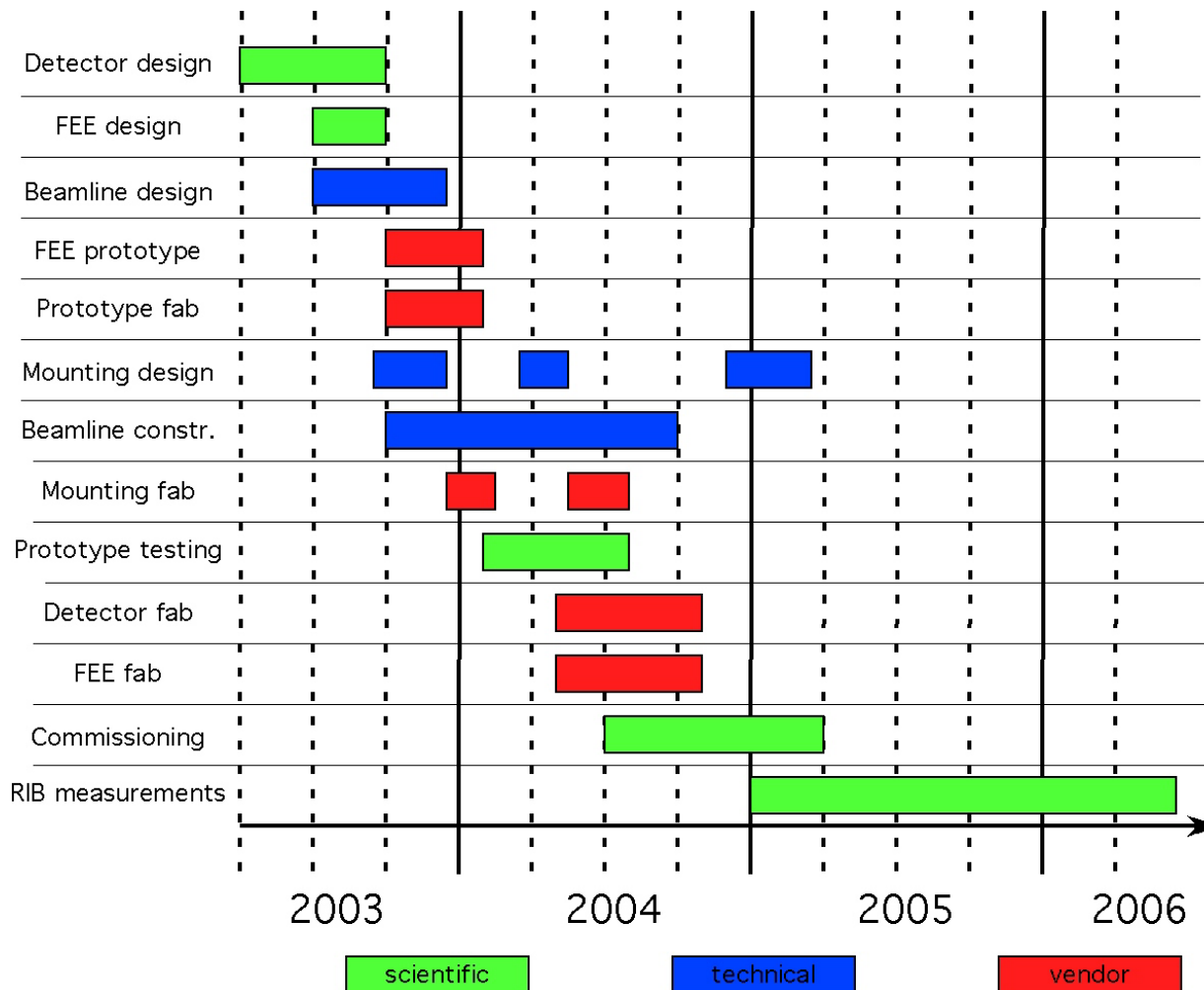
Major Milestones

1/31/04
  Prototype complete

10/31/04
  Full array complete

3/31/05
  First RIB experiment

Providing data for stewardship science

- Understand neutron fluxes and fission yields
- Measured long-lived daughters of reaction products
    - Nuclear reactions on radiochemical detectors
    - **Decay products from fission**
- Intense source of neutrons
    - Multiple neutron-induced reactions
- Challenge: Understanding neutron reactions on isotopes far from stability

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Fission Products and Their Decay

94,95Sr

137,138Xe

87,88Se

102,103Zr

131Sn

146Ba
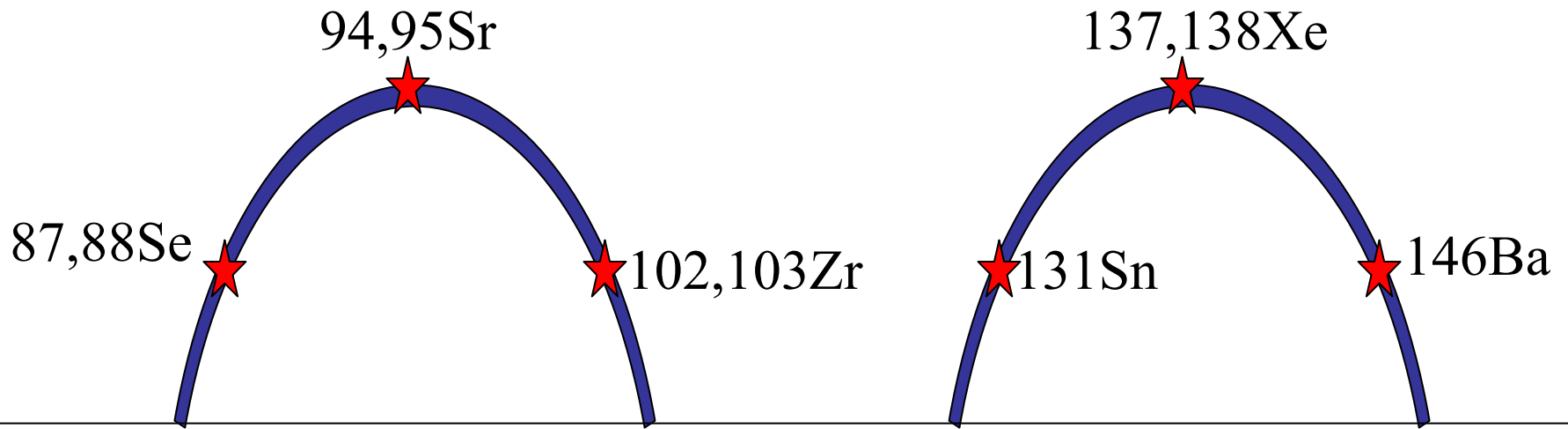
235U Fission

Determining Fission Yields

- ^{95}Sr - near peak of ^{235}U fission yield
  - $t_{1/2}$ = 24s
- Measure yield of daughter ^{95}Zr
  - $t_{1/2}$ = 64 days
- Challenge: neutron-induced reactions on unstable species near A=95
- Example: Network calculation by Mark Stoyer, LLNL

A=95 region

Known cross-sections

IY (fs) > 0.5%
^{235}U, ^{238}U, ^{239}Pu
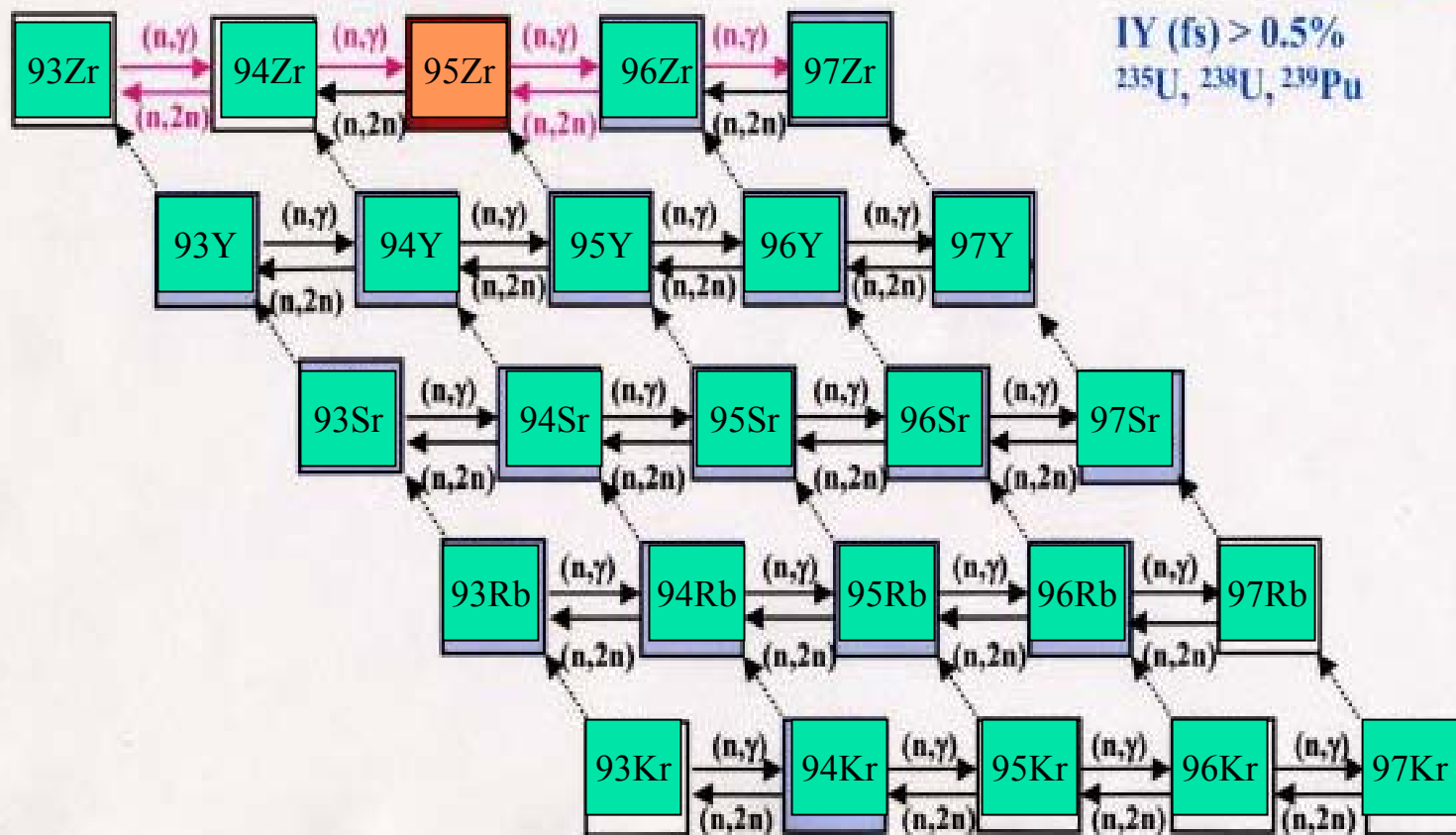
Multiple neutron reactions -
Challenges to interpreting radiochemical results

- ^{95}Zr as measure of fission yield

- Many (n,γ) and (n,2n) reactions on unstable species affect predictions of ^{95}Zr yields
  - Zr isotopes and prompt fission fragments
  - Other beta decay daughters of fission fragments

- Stoyer found unknown ^{95}Sr(n,γ) cross section particularly sensitive to resultant yield

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Los Alamos Fission Fragments for Modeling

- Use 19 fission fragments for modeling neutron-induced reactions following ^{235}U and ^{239}Pu fission

- 235U

  - ^{94,95}Sr, ^{87,88}Se, ^{102,103}Zr

  - ^{131}Sn, ^{138,139}Xe, ^{146}Ba

- 239Pu

  - ^{93,94}Kr, ^{99,100}Zr, ^{107,108}Mo

  - ^{130}Sn, ^{137,138}Xe, ^{145}Ba

Challenge: Unstable beam developments

- **Many neutron-rich fission fragment beams,** *but*
    - Need to improve beam purity
    - Need to improve beam intensity
    - Current work: enhance Sr beams
- Future: proton-rich beams of applied interest
    - Radiochemical detectors

Developing/Improving Unstable Beam Production

3- Ionize atoms

4- Create Negative Ions

2- Transport to ion source

1- Create nucleus of interest
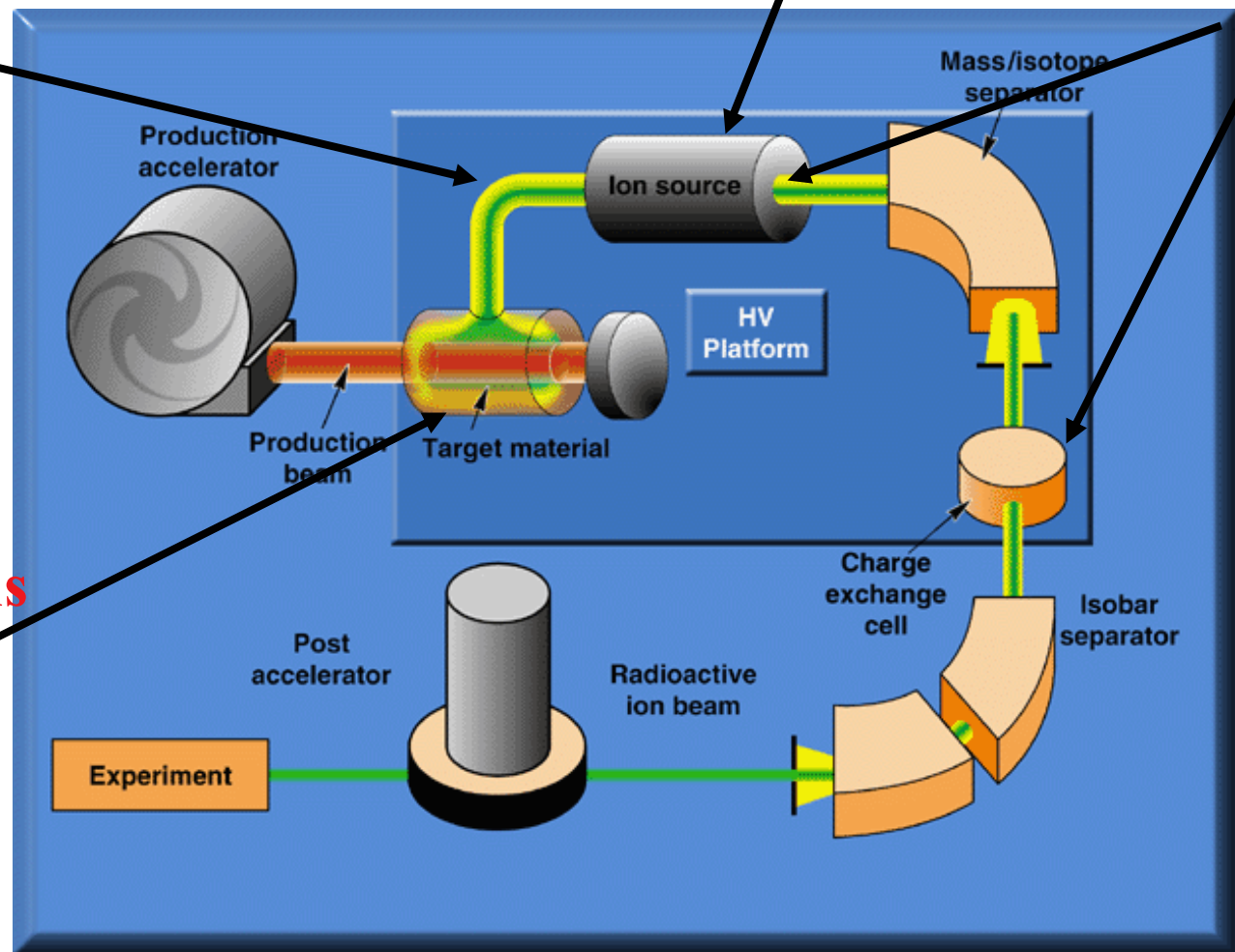
Unstable beam developments

- Ken Carter + PD + technician

- UNISOR test bench to enhance unstable ion beam capabilities
  - Enhanced isobaric purity
  - Enhanced intensities
  - New unstable beam capabilities

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Long Term:
Rare Isotope Accelerator - RIA

- Enable (d,p) reaction measurements
  - Further from stability
  - Greatly increased intensity
- Enable nuclear spectroscopy studies of nuclei on proton-rich side
- Enable direct (n,γ) measurements on unstable species near stability -
  - Mining of radioisotopes?
  - High intensity neutron generator at RIA site?

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From a Multibeam Driver, Mass Separated Intensities (pps)

400 MeV/u

100 kW

Z=50

Z=32

N=82

N=50

Proton Number

Neutron Number

Stable Isotopes
$> 10^{12}$
$10^{10}\text{-}10^{12}$
$10^{8}\text{-}10^{10}$
$10^{6}\text{-}10^{8}$
$10^{4}\text{-}10^{6}$
$10^{2}\text{-}10^{4}$
$1 \text{ -}10^{2}$
$10^{-2}\text{- }1$
$10^{-4}\text{-}10^{-2}$
r - process

January 2004

UNIRIB
University Radioactive Ion Beam Consortium

CENTER OF EXCELLENCE FOR
RADIOACTIVE ION BEAM STUDIES
FOR STEWARDSHIP SCIENCE

THE STATE UNIVERSITY OF NEW JERSEY
RUTGERS
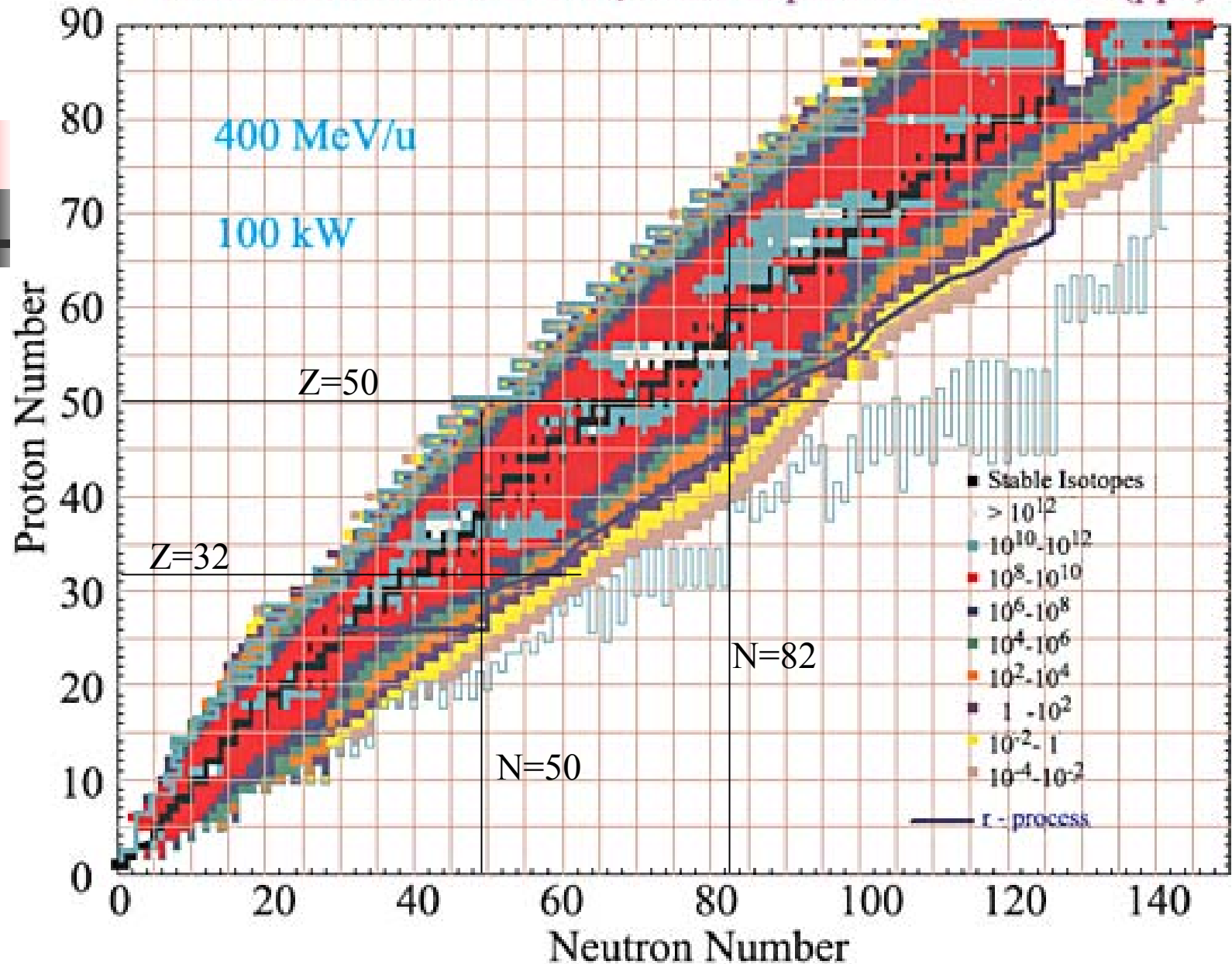
Transfer reactions at HRIBF

J.A.C., K. L. Jones, J. S. Thomas
Rutgers University
D. W. Bardayan, J. C. Blackmon, C. J. Gross, F. Liang, D. Shapira, M. S. Smith
Oak Ridge National Laboratory
R. L. Kozub, B. H. Moazen, C. D. Nesaraja
Tennessee Tech. University
H.K. Carter, M. S. Johnson
Oak Ridge Associated Universities
U. Greife, R. J. Livesay
Colorado School of Mines
A. Champagne, R. Fitzgerald
University of North Carolina, Chapel Hill
Z. Ma
University of Tennessee
Phil Woods, Tom Davinson
University of Edinburgh, UK
W. Catford
University of Surrey, UK
R.V.F. Janssens, E. Rehm, J.P. Schiffer
Argonne National Laboratory
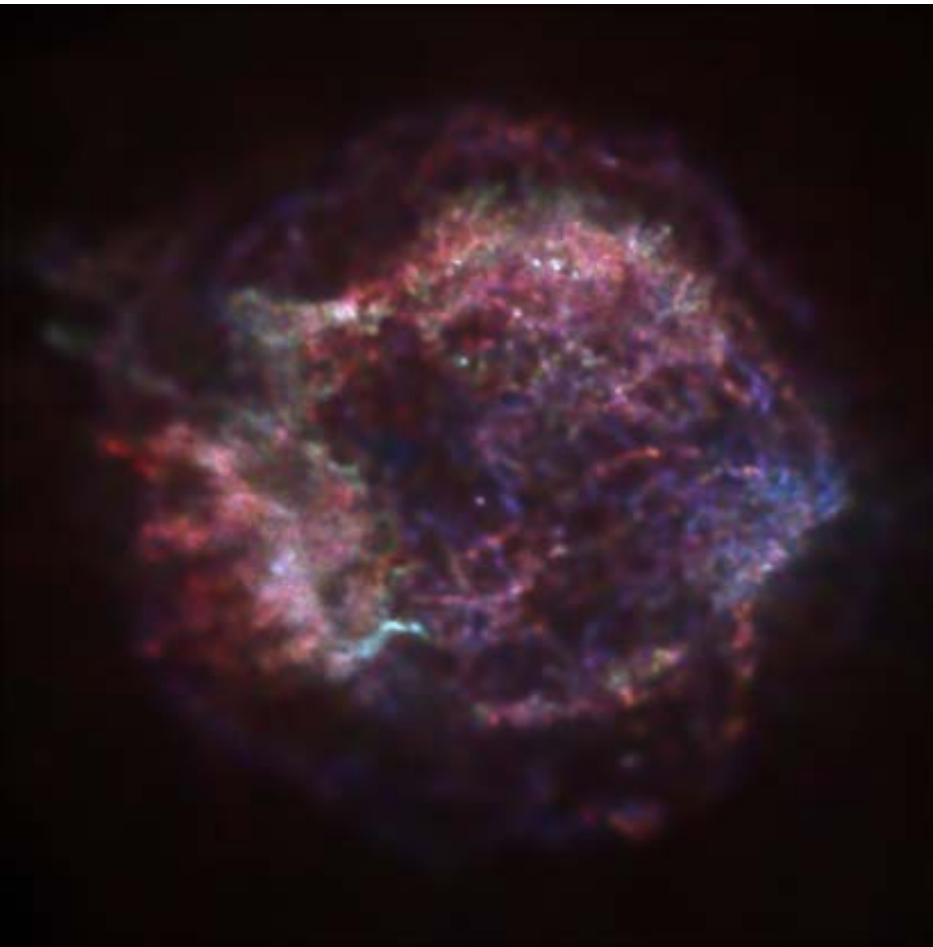
Status of the Project

- Unstable beam (d,p) measurements:
  - Initial A≈80 measurement complete
    - Measuring ^{84}Se(d,p) today
  - Developing A≈130 capabilities
    - Prepared to measure ^{130,132}Sn (d,p)
  - ^{92,94}Sr (d,p) approved; measure in 2004
- New array of silicon detectors
  - Specs for prototype detector; order early 2004
  - First experiments with array in early 2005
- Improving unstable beams; Sr in summer 2003
- **Need theoretical help**
  - Shell model calculations
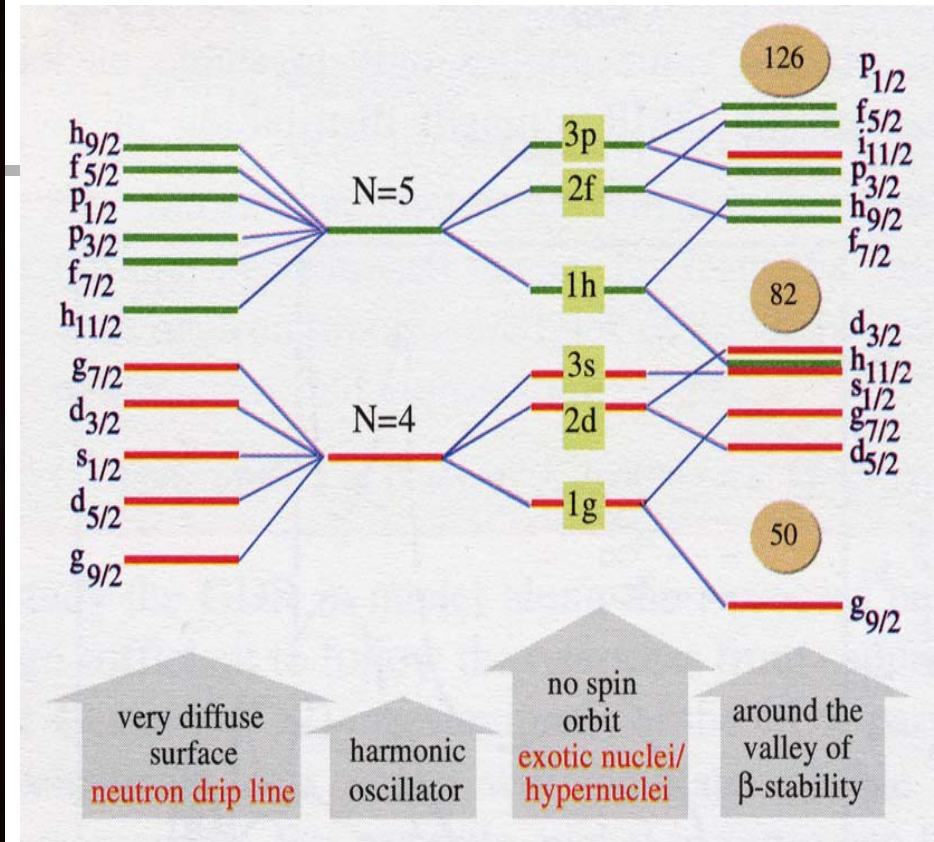 - Taking (d,p) results to inform $\sigma(n,\gamma)$

Requests from you

- ## Help with theoretical development
  - Using (d,p) results to inform (n,γ) cross sections
  - Interpreting single-particle strengths far from stability

- ## Help with experimental measurements

- ## Collaborators are welcome

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Origin of the Heavy Elements?

Evolution of Nuclear Shells?

Stewardship Science

Direct Capture
^{36}S(n,γ) and ^{36}S(d,p)

Thermal capture

(d,p)
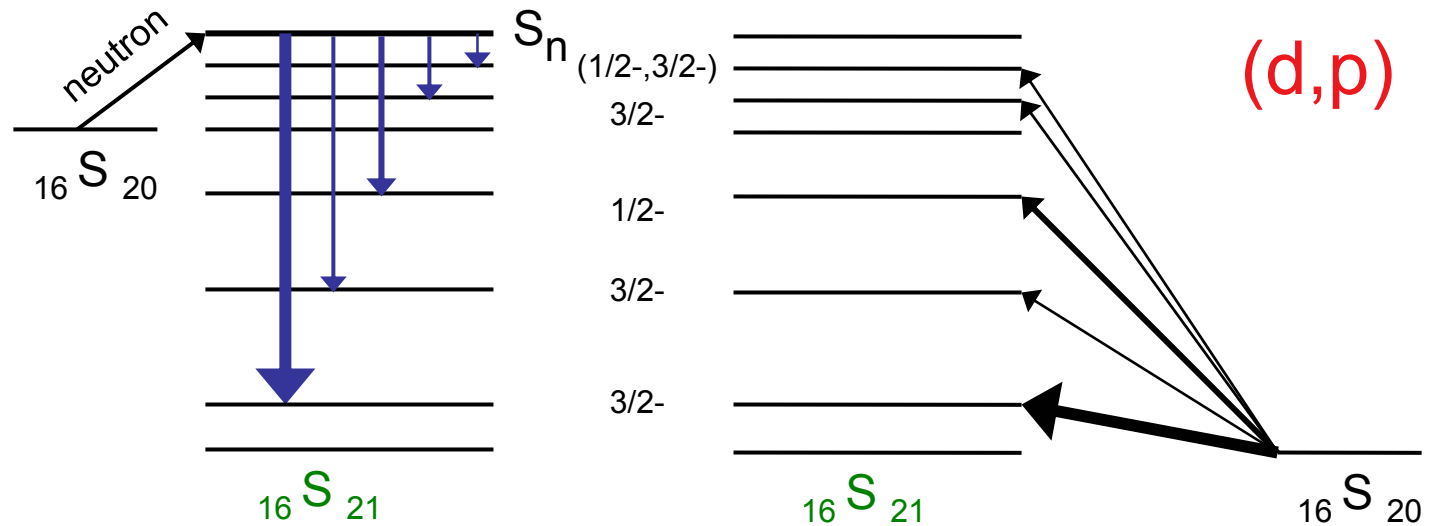
$\sigma_\gamma \approx \sigma$(hard sphere) *C*

σ(hard sphere) ≈ (2J+1) Spectroscopic factor
Depends on E_n, E_γ, scattering length ≈3fm

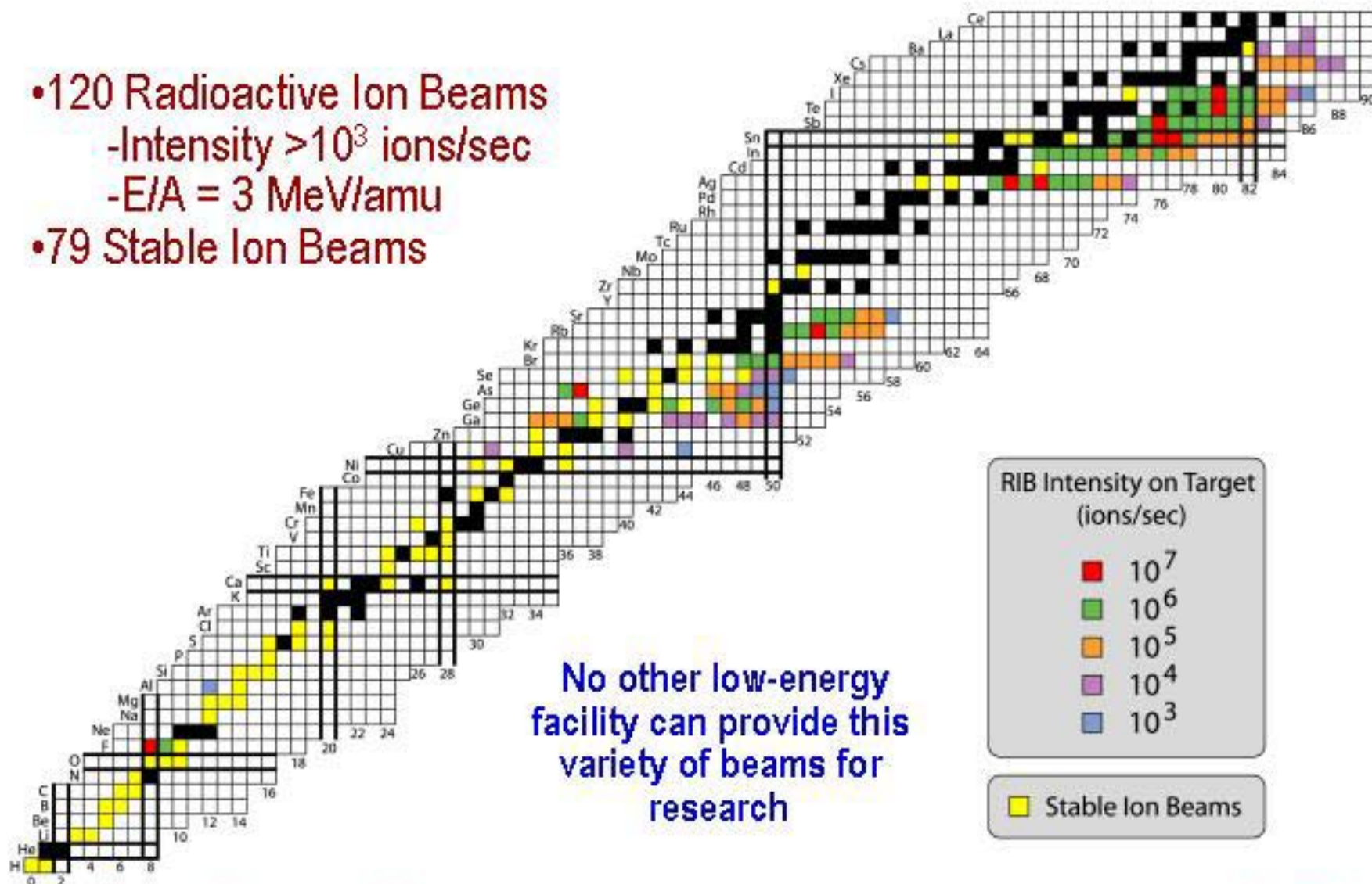Raman, et al., (exp); Lane and Lynn (thy)

Jolie's to do

- ## 95Zr properties
  - $t_{1/2}$ = 64 days
- ## Thesis figures
  - Schematic of (n,g)
  - Sc neutron cross sections
- ## Can I find total cross sections up to high energy, to see when (n,2n) comes in?
  - I.e., what are "bomb thermal" energies
- ## Have 69,70As beams and unstable Ga

Accelerated Ion Beams Now Available at the HRIBF
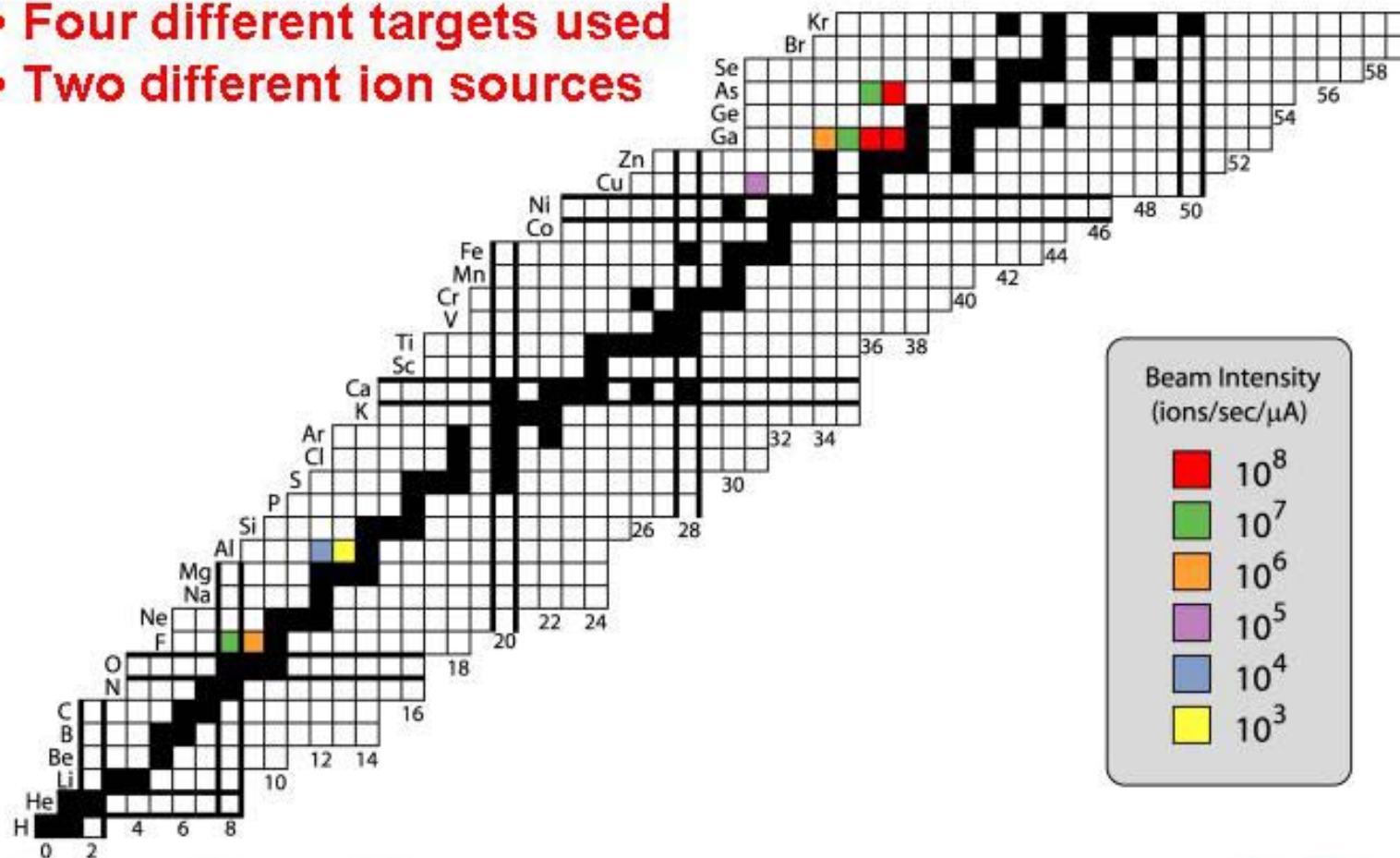
- 120 Radioactive Ion Beams
  - Intensity $> 10^3$ ions/sec
  - E/A = 3 MeV/amu
- 79 Stable Ion Beams

No other low-energy facility can provide this variety of beams for research

RIB Intensity on Target (ions/sec)

- ■ 10^7
- ■ 10^6
- ■ 10^5
- ■ 10^4
- ■ 10^3

□ Stable Ion Beams

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9

Proton-rich Radioactive Ion Beams

- **Four different targets used**
- **Two different ion sources**

Beam Intensity (ions/sec/µA)

🟥	10^8
🟩	10^7
🟧	10^6
🟪	10^5
🟦	10^4
🟨	10^3

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